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DESIGN REPORT
FOR
RL10A-3-1 ROCKET ENGINE

CONTRACT NO. NAS8-5623

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Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION

FLORIDA RESEARCH & DEVELOPMENT CENTER

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DESIGN REPORT

FOR

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FOREWORD

This report describes the RL10A-3-1 Rocket Engine, and is submitted in compliance with the requirements of Contract NAS8-5623, Exhibit A, Item 4, paragraph f.

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(Continued)

ILLUSTRATIONS

ILLUSTRATIONS
(Continued)

PREFACE

This report describes the design features of the RL10A-3-1 rocket engine. The following sections are included in this report in accordance with the requirements of Contract NAS8-5623, Exhibit A, Item 4, paragraph f.

I. Component design analysis
II. Installation drawing
III. Assembly drawing
IV. Weight breakdown
V. Analysis of steady-state and transient performance
VI. Schematic drawing
VII. Materials glossary
VIII. Engine Parts List
IX. Propellant and ancillary fluid pressure and temperature requirements
X. Malfunction analysis

The engine configuration described herein incorporates design changes through 1 June 1964.

Information contained in this report also applies to the RL10A-3-CM-1 engine; the major functional difference between the two models is that the RL10A-3-1 engine incorporates a single transducer box while the RL10A-3-CM-1 has two transducer boxes.

SECTION I
DESCRIPTION OF COMPONENT DESIGN

A. PROPELLANT CONTROL SYSTEM

The RL10A-3-1 propellant control system consists of the following components: fuel pump inlet shutoff valve, oxidizer pump inlet shutoff valve, oxidizer flow control valve, prelaunch cooldown and check valve, fuel pump cooldown and bleed valves (interstage and discharge), thrust control, main fuel shutoff valve, prestart and start solenoid valves, igniter, and oxidizer supply control valve. A schematic of the propellant system is shown in Section VI, figure VI-1.

1. Propellant Inlet Shutoff Valves

The propellant inlet shutoff valves provide a seal between the vehicle tanks and the engine pumps during nonfiring periods, and open fully upon application of the prestart signal. The propellant pump inlet shutoff valves are helium-operated, two-position, ball-type normally closed valves. (See figure I-1.)

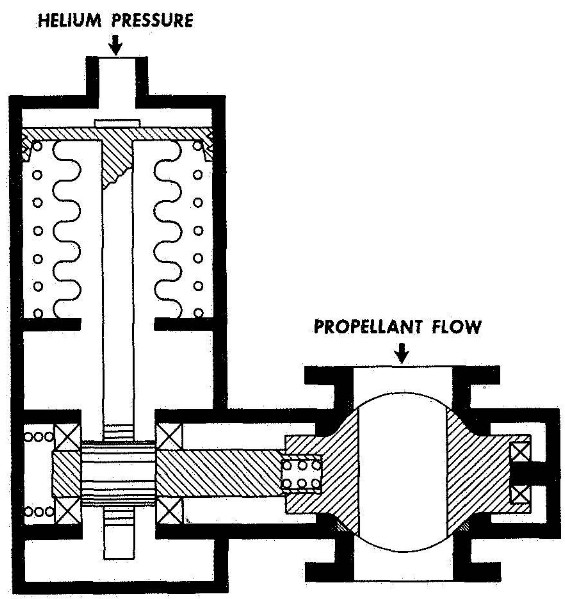


Figure I-1. Propellant Pump Inlet Shutoff Valve Schematic FD 3145

At the prestart signal, vehicle-supplied helium pressure acts upon the piston to overcome the resistance of the valve spring and to provide a linear motion to the rack. This produces rotational motion at the ball valve, and as the ball is rotated to the open position, propellants are allowed to pass through the valves into the pumps. The elapsed time from the closed to the fully open position is approximately 17 milliseconds for the oxidizer inlet shutoff valve, and approximately 30 milliseconds for the fuel inlet shutoff valve.

When the actuating helium pressure is vented, the ball valve is returned to its normally closed position by the compressed spring and the helium boosted piston which gets its boost by leakage past the piston ring seal. The elapsed time from the fully open to the closed position is approximately 158 milliseconds for the oxidizer inlet shutoff valve, and approximately 389 milliseconds for the fuel inlet shutoff valve.

The bellows assembly acts as a seal between the rack and gear chamber, which is exposed to propellant, and the spring chamber, which is exposed to helium.

When the valve is in a closed position, Belleville washers and the line pressure maintain a positive sealing load on the seal located at the valve exit.

The drive gear and valve ball are ball-bearing mounted and are positioned axially by springs that maintain a constant thrust load for longer bearing life. Specifications for the fuel and oxidizer pump inlet shutoff valves are given in Appendix D.

2. Fuel Pump Cooldown, Bleed and Pressure Relief Valves

The cooldown valves (figure I-2) provide (1) overboard venting of fuel during prestart to cool down both fuel pump stages, (2) fuel bleed at interstage during acceleration to provide transient stability, and (3) a pressure relief during engine shutdown. The interstage and discharge valves are similar in function.

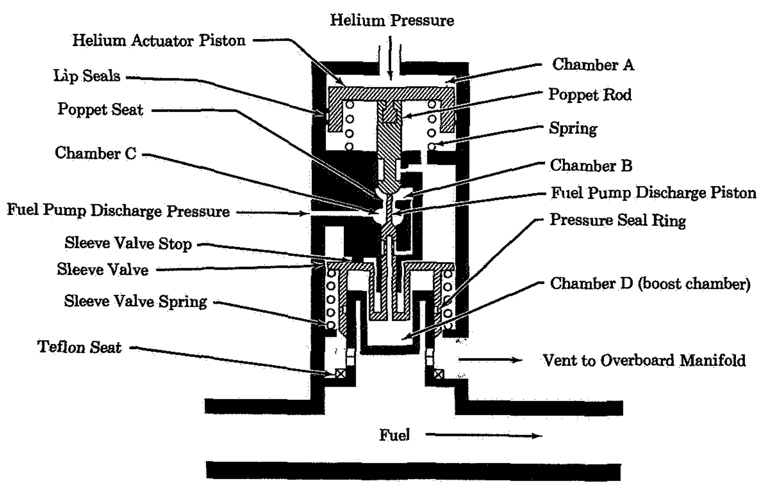


Figure I-2. Pressure-Boosted Fuel Pump Cooldown, Bleed and Pressure Relief Valve Schematic FD 2666B

a. Fuel Pump Interstage Cooldown Bleed and Pressure Relief Valve

The fuel pump interstage cooldown bleed and pressure relief valve is a pressure operated, three-position, sleeve-type, normally open valve. The first position, which is the normally open position of the sleeve valve, produces maximum overboard venting. When the fuel prestart helium pressure signal initiates the cooldown cycle, the fuel inlet valve opens and allows fuel to pass through the first stage of the fuel pump and a portion of the flow passes overboard through the interstage cooldown valve.

At the start signal, helium pressurizes chamber "A" and actuates the piston. Redundant lip seals minimize the piston clearance leakage. After 0.2 inch of travel the poppet is seated, sealing the pump discharge pressure chamber "C" from the overboard vent and from the pump discharge pressure transfer chamber "B."

As the poppet rod is moving, the fuel pump discharge piston moves. This, in turn, moves the fuel pump discharge sleeve valve and partially closes the three overboard vent ports. At this point the interstage valve area is reduced approximately 40%. This second position, which is the bleed position, allows overboard flow during the early stages of acceleration to help prevent low-speed pump stall. As fuel pump pressure increases during acceleration, the sleeve valve overcomes the valve spring load, and in the fully closed position seats against the Teflon ring seal.

Fuel pump discharge pressure acting on the fuel pump discharge piston in chamber "C" causes the sleeve valve to move to its third or closed position. Fuel pressure in chamber "B" and "D" is vented overboard by porting the poppet rod and the fuel pump discharge piston. This ensures that any leaks of fuel pump discharge pressure from chamber "C" into chambers "B" and "D" would not oppose movement of the sleeve valve. In addition, a seal ring between the post and the sleeve valve prevents leakage through this path from pressurizing chamber "D."

The valve incorporates a boost feature that accelerates its return to the fully open position during shutdown. As the pressure in the helium supply system decays during shutdown, the actuator spring and fuel pump discharge pressure in chamber "C" acting on the poppet furnish the force to unseat the piston valve.

The return motion of the actuator piston opens the poppet valve and allows fuel pump discharge pressure to enter chamber "D" and act on a larger area than the fuel pump discharge piston area. This creates a greater opening force to move the sleeve valve to its normally open position.

The interstage sleeve valve is in the fully open position approximately 13 milliseconds after the poppet valve is unseated. This fast response provides the pressure relief function by venting the fuel system prior to inlet and main fuel shutoff valve closure.

b. Fuel Pump Discharge Cooldown Bleed and Pressure Relief Valve

The fuel pump discharge cooldown bleed and pressure relief valve is a pressure operated, two-position, sleeve-type, normally open valve.

The first position, which is the normally open position of the sleeve valve, produces maximum overboard venting. When the fuel prestart helium pressure initiates the cooldown cycle, the fuel inlet valve opens and allows fuel to pass through the pump and overboard through the discharge cooldown valve.

At the start signal the discharge valve moves in identically the same manner as the interstage valve. The only difference being that the entire port is closed off by this initial motion. The travel is the same, 0.2 inch. As fuel pump pressure increases during acceleration, the sleeve valve overcomes the valve spring load, and seats against the Teflon ring seal.

All internal sealing, venting, and boosting features of the discharge valve are identical to those in the interstage valve. At shutdown, the discharge valve is fully opened in approximately 19 milliseconds.

3. Prestart and Start Solenoid Valves

The prestart and start solenoid valves (figure I-3) are solenoid actuated, double-ended poppet valves that control the helium supply from the vehicle storage tank to the propellant control valves. The two solenoid valves are identical in design, operation, and construction.

The prestart solenoid valve controls the helium supply to the fuel and oxidizer inlet shutoff valve actuators, which open before start to permit cooling of the fuel and oxidizer pumps.

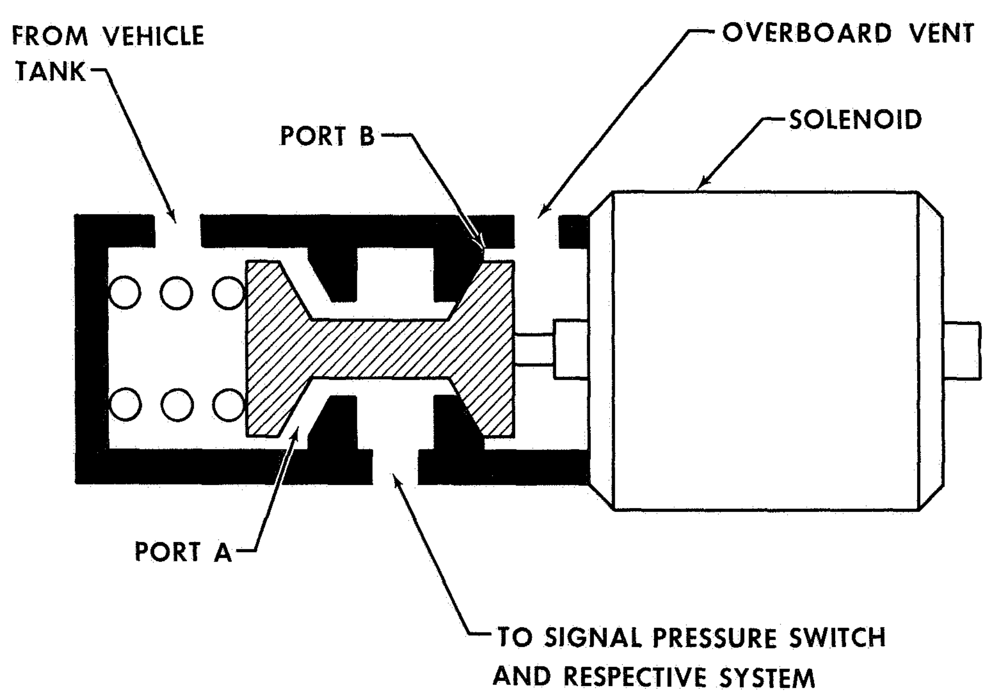


Figure I-3. Solenoid Valve Schematic FD 4444

The start solenoid valve controls the helium supply to the main fuel shutoff valve and the fuel pump bleed-cooldown and pressure relief valve actuators.

The helium supply system and the solenoid valves are shown in the schematic in Section VI.

In the de-energized position, valve port "A" is closed and valve port "B" is in the open position. The poppet is positioned by the force of the valve spring upon the poppet valve body. At either the prestart or the start signal, the respective solenoid is energized by the vehicle dc voltage supply, and the plunger rod moves the poppet valve to a position such that port "A" is open and port "B" is fully closed. Helium is supplied to the respective control system component through valve port "A."

At shutdown, the solenoid is de-energized and the valve spring returns the valve body to a position that closes valve port "A" and opens port "B."

Controlled selection of the poppet during valve assembly maintains a proper closing response time of the solenoid and desirable actuation of the start and prestart valves.

Each of the solenoids is directly connected to the vehicle wiring, eliminating the need for a solenoid wiring harness. The positive ground used on each solenoid valve housing also reduces the level of radio interference.

4. Main Fuel Shutoff Valve

The function of the main fuel shutoff valve (figure I-4) is to prevent the fuel flow into the thrust chamber during cooldown periods and to stop fuel flow into the thrust chamber at shutdown. During engine operation at the design point, the fuel flow rate is 5.85 pounds per second with a valve pressure drop of 10 psi.

The main fuel shutoff valve is a helium-operated, two-position, normally closed, bullet-type valve. At the start signal, vehicle supplied helium pressure acts upon the internal effective area of the bellows to overcome the resistance of the valve spring and actuates the valve gate. The exterior of the bellows is vented overboard and sealed from fuel by a lip seal. Actuating the valve gate opens a flow passage through the valve housing permitting fuel to flow into the injector. After removing the helium pressure, the valve gate is returned to its normally closed position by the compressed spring. Sealing is accomplished by spring loading a spherical surface on the gate against a conical surface on the valve housing and by the gate seal ring. The fuel inlet shutoff valve provides the necessary sealing between the vehicle and the fuel pump; therefore, zero leakage of this valve is not required.

The bullet valve configuration was selected because it is light in weight and provides the fast response necessary for adequate control of shutdown impulse.

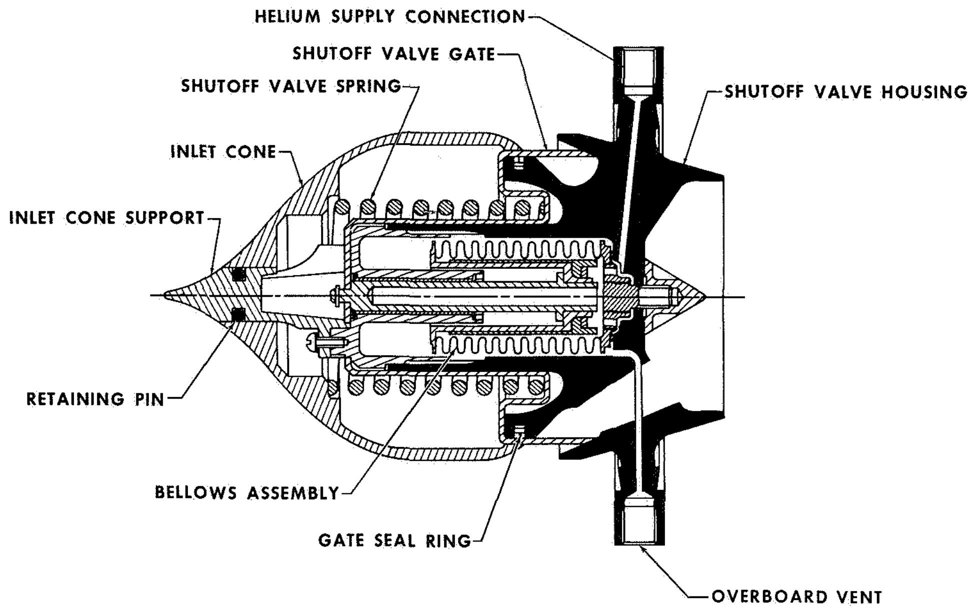


Figure I-4. Main Fuel Shutoff Valve Schematic FD 1551B

5. Oxidizer Flow Control and Pressure Relief Valve

The functions of the oxidizer flow control and pressure relief valve shown in figure I-5 are as follows:

a. Maintain the required oxidizer flow during the cooldown cycle
b. Control the oxidizer-to-fuel ratio during the start cycle
c. Permit ground trim of mixture ratio
d. Provide a means for vehicle control of the consumption of oxidizer for optimum utilization of propellants.

The oxidizer flow during engine cooldown is controlled by the variable-area orifice "A_1" and the fixed-area orifices "A_2" and "A_3." For maximum pressure inlet conditions, the variable-area orifice is closed and the full bypass flow passes through the fixed-area orifices "A_2" and "A_3." This provides the additional feature of cooling the valve uniformly to ensure proper valve operation. As the inlet pressure decreases, the variable-area orifice opens to provide additional bypass area.

Orifice "B," which is controlled by the inlet poppet valve, is fully closed during cooldown and during the initial portion of the start cycle. The controlled oxidizer flow is necessary to maintain the proper oxidizer-to-fuel ratio for proper engine acceleration.

The back face of the inlet poppet valve senses pump inlet pressure and the upstream surface is subjected to pump discharge pressure. A pressure differential of 40 to 60 psi will overcome the spring preload and open orifice "B." The amount of preload can be varied by adjustment screw "Y." The area opened at orifice "B" during acceleration is a function of the valve contour and the oxidizer pump pressure rise. The maxium area is regulated by an adjustment stop that can be remotely controlled during an acceptance test. The valve is designed to flow 29.3 lb/sec at a pressure drop of 102.4 ± 16 psi and a mixture ratio of 5 to 1. The ± 16 psi tolerance results from accumulative engine system tolerances and is accounted for in the engine trim.

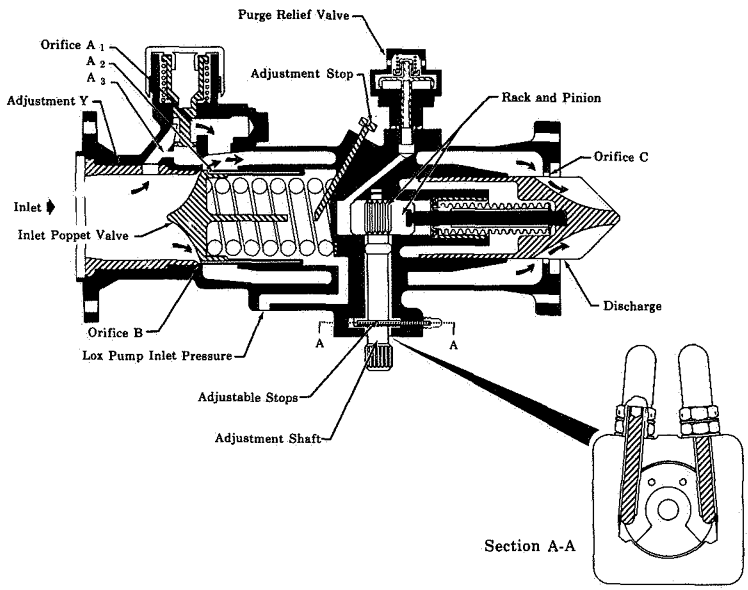


Figure I-5. Oxidizer Flow Control and Pressure Relief Valve Schematic FD 2200D

The oxidizer flow control and pressure relief valve incorporates provisions to mount a drive motor that is controlled by the vehicle propellant utilization system. This motor drives an adjustment shaft that controls orifice "C." This adjustment shaft incorporates adjustable stops providing for limiting adjustment shaft movement to limit the mixture ratio range to allowable values. The motor and shaft assembly are sealed from oxidizer flow and are purged with dry nitrogen prior to flight to prevent ice from restricting motion of the adjustment shaft. During acceptance testing, engines are trimmed to a mixture ratio of 5.0 ± 0.1 with the positioner shaft in the mid-position. This is accomplished by maintaining the vehicle indexing point on the adjustment shaft at nominal position, and trimming the oxidizer flow by varying orifice "B;" the adjustment of orifice "B" is then locked. The vehicle positioner can then vary orifice "C" to minimize residual fuel or oxidizer at burnout.

6. Thrust Control Valve

The thrust control valve (figure I-6) is a servo-operated variable-position valve that controls engine thrust by regulating the amount of fuel that bypasses the turbine as a function of combustion chamber pressure. This, in turn, controls the speed of the turbopump.

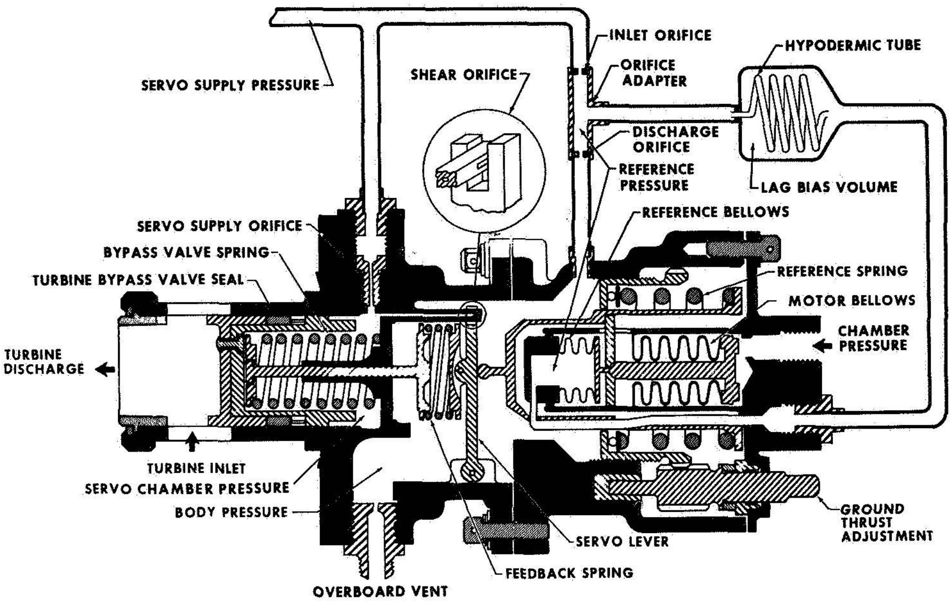


Figure I-6. Thrust Control FD 6769

The reference system carriage position is determined by: (1) the combustion chamber pressure acting on the area of the motor bellows; (2) the reference spring preload (approximately 55 lbs), which can be remotely adjusted during engine calibration by the thrust lever (preload) adjustment to provide a nominal combustion chamber pressure of 300 psia; and (3) pressure differential acting on the reset bellows area.

The reset bellows internal pressure is supplied from the orifice adapter body through the pneumatic reset orifice-volume into the reset bellows. This causes reset pressure to lag orifice adapter body pressure during engine acceleration; thus producing a force that allows the carriage to be positioned to a nominal position before chamber pressures reach the normal 300 psia. This actuates the servolever, which bleeds chamber pressure and opens the turbine bypass area before engine nominal conditions are reached, thus reducing thrust overshoot. The orifice adapter is supplied with servosupply pressure and vented into the thrust control body. The external orifice adapter was chosen so that the reset bellows pressure would be relatively unaffected by temperature changes in the servosupply.

The bypass valve is spring-loaded in the closed position and senses turbine discharge pressure and servochamber pressure. Servochamber pressure is supplied through an orificed line from the heat exchanger discharge passage and is bled into the body through a shear orifice servovalve, which was selected for its stability feature. Body pressure is bled overboard through an orifice sized to give the desired pressure. When servochamber pressure is reduced by opening of the servovalve, the increased pressure differential acting on the bypass valve is sufficient to overcome the valve spring force and the valve is repositioned. This uncovers the contoured bypass ports which permit flow to bypass the turbine.

The servovalve lever position is maintained by a force balance of the reference system which reflects chamber pressure and the feedback spring which reflects bypass valve position. A change in chamber pressure will produce a force unbalance that varies the position of the servovalve, which causes a proportional variation in servochamber pressure. This pressure variation repositions the bypass valve, which alters the feedback spring force until the force balance is regained.

Repositioning of the bypass valve varies turbine power which establishes total propellant flow, chamber pressure, and thrust.

7. Igniter Oxidizer Supply Control Valve

The igniter oxidizer supply control valve (figure I-7) provides a gaseous oxygen flow to the spark igniter.

At the prestart signal, helium pressure opens the propellant inlet shutoff valve and permits the oxidizer to flow to one side of the igniter oxidizer supply valve. Minimum inlet pressure conditions are sufficient to actuate the piston and unseat the poppet, permitting a flow of gaseous oxygen, which is bled from the supply line to the injector, to enter the combustion chamber near the spark igniter tip.

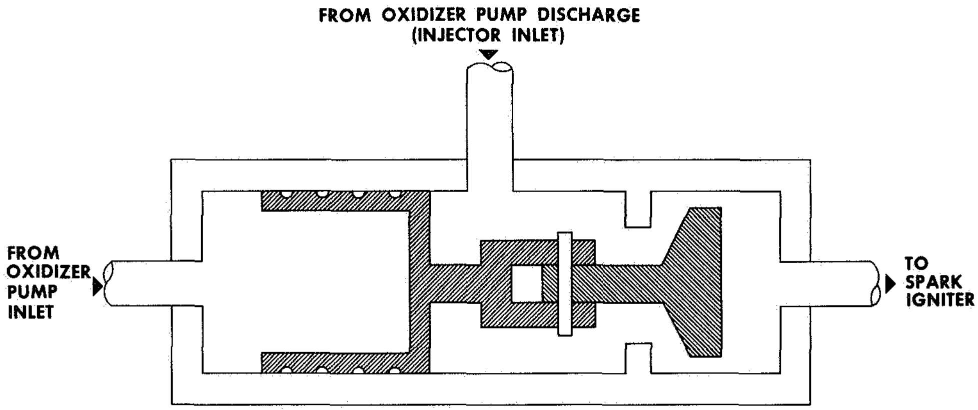


Figure I-7. Igniter Oxidizer Supply Control Valve Schematic FD 3161

At the start signal, the main fuel shutoff valve opens and allows fuel to flow into the combustion chamber where it is ignited. The increase in oxidizer pump discharge pressure is transmitted to the opposite end of the igniter oxidizer supply control valve piston and closes the poppet to stop the flow of gaseous oxygen to the spark igniter.

8. Prelaunch Cooldown Check Valve

The RL10A-3-1 engine is fitted with a check valve (figure I-8) for introduction of cold helium into the turbopump prior to vehicle launch. This partially cools the turbopump before vehicle launch.

In the open position, the valve allows liquid helium from a test stand or vehicle supply at 15-40 psig to flow into the first stage fuel pump and fuel pump shaft seal cavity. The helium is then discharged

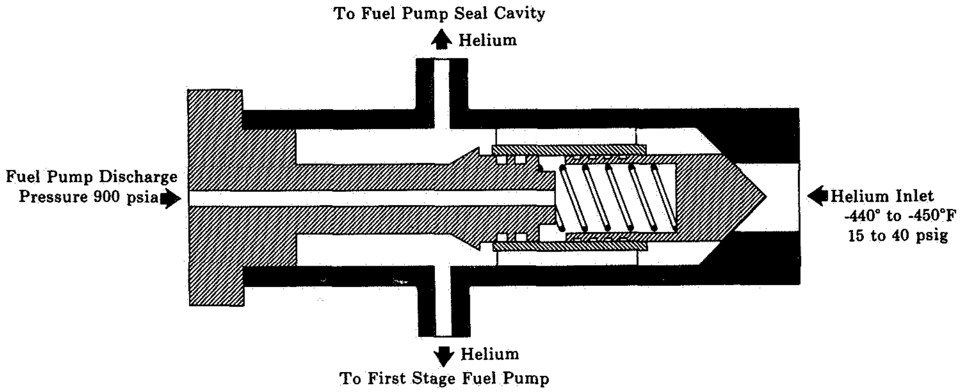


Figure I-8. Prelaunch Cooldown Check Valve FD 7367

overboard through the gearbox relief valve and fuel bleed-cooldown valves. When the helium supply is removed, the check valve is closed by spring force, augmented by fuel pump discharge pressure as the engine accelerates.

B. TURBOPUMP ASSEMBLY

The turbopump assembly (figures I-9 and I-10) consists of: (1) a two-stage centrifugal liquid hydrogen pump that is driven by a two-stage hydrogen turbine mounted on a common shaft; and (2) a single-stage centrifugal liquid oxygen pump that is mounted side-by-side with the liquid hydrogen pump, and is driven by a gear train from the main shaft. The three shafts in the turbopump assembly are mounted on hydrogen-cooled, unlubricated ball and roller bearings. The complete assembly is housed in six aluminum castings. An adapter has been added to permit checking of turbopump static torque with the vehicle hydraulic pump installed on the accessory drive pad.

1. Fuel Pump

The fuel pump is a two-stage centrifugal-type pump that has back-shrouded impellers, volute collectors, and conical diffusers. The two stages are mounted back-to-back to minimize the thrust unbalance carried by the interstage ball bearing. The open-face impeller design results in lower weight, fewer sealing problems, and a more simple impeller construction than a fully shrouded type. The pump has a collecting volute and a straight conical diffuser for recovery of the velocity head. The 1st-stage pump is preceded by a three-bladed axial flow inducer that operates at the same speed as the main impeller. The NPSP capability is controlled by the inducer. The RL10A-3-1 uses inducer blades that are tapered at inlet and exit. This type of inducer, which is sometimes termed a propeller-inducer, is the end product of a program to develop an inducer that would allow a maximum extension of the operating range to the high flow region without adversely affecting the low flow characteristics, and the ability of the pump to operate at the minimum design NPSP.

The 1st-stage impeller incorporates 50-degree exit angle, backswept blades. The 2nd-stage impeller has 90-degree exit angle blades. Clearance between the impeller blading and the housings is a nominal 0.060 inch. This configuration provides the required match between stall margin, which is improved with increased blade sweep angle, and required headrise, which decreases with increased vane sweep angle.

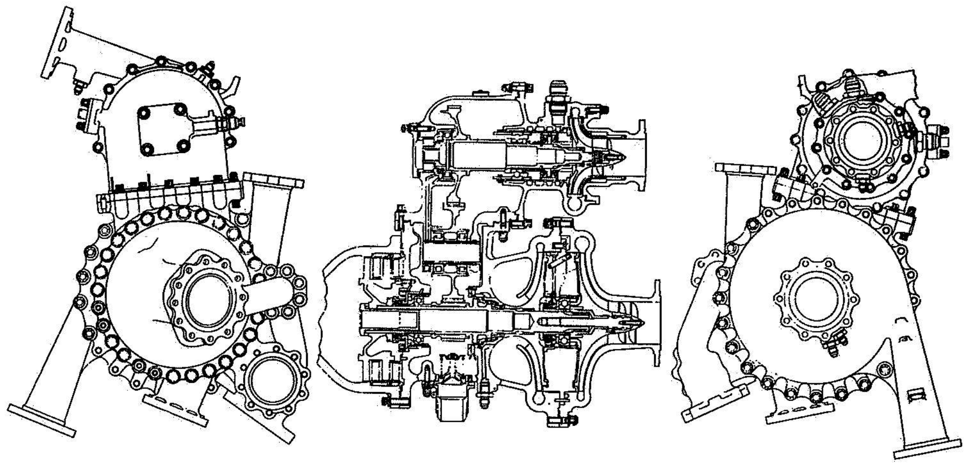


Figure I-9. Turbopump Assembly FD 1510A

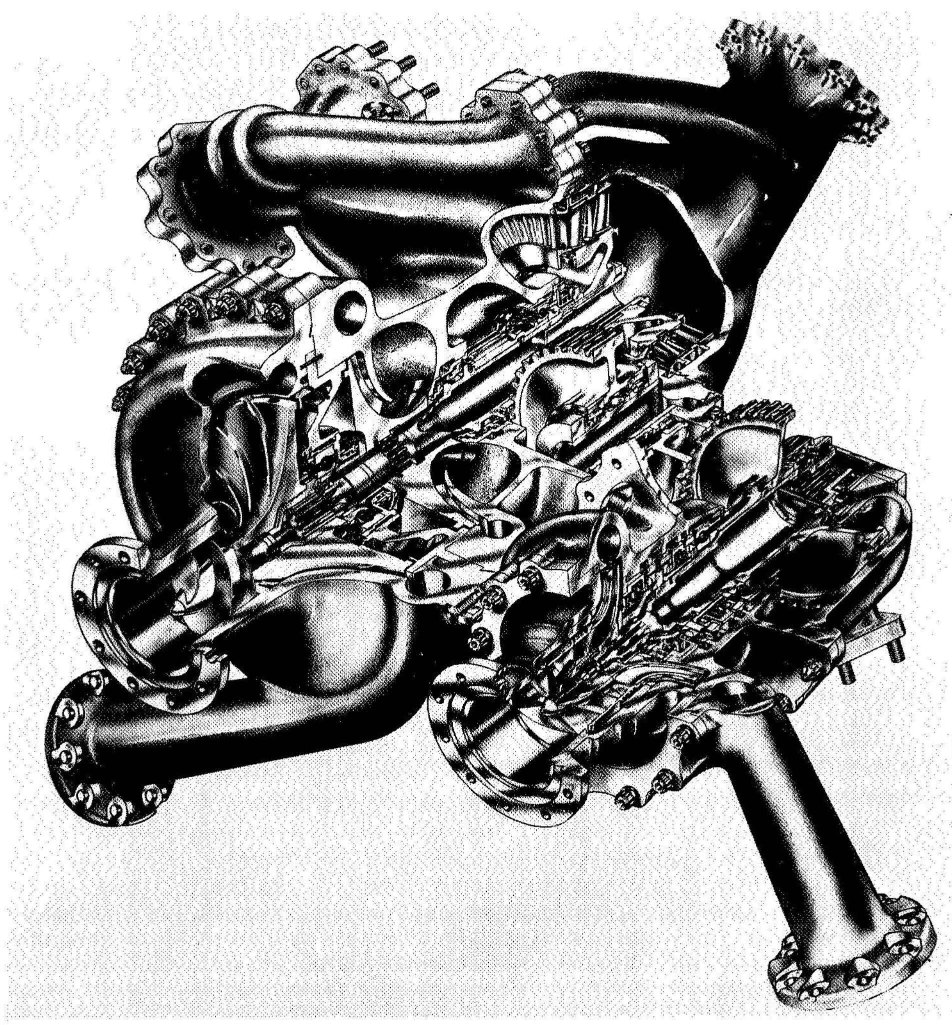


Figure I-10. Turbopump Cutaway FD 3261

An orifice is placed downstream of the pump discharge cooldown valve to isolate the pump from the pressure surges that the engine experiences during start, and thus ensure stable engine operation. This orifice has a diameter of 0.813 in., and a pressure drop of 78.4 psia at nominal engine operating conditions.

The fuel pump was designed to operate at 30,000 rpm with a minimum net positive suction head of 264 feet of hydrogen. The present operating point for the pump is 28,400 rpm and will provide a minimum weight flow of 5.85 lb/sec with a head rise of 29,300 feet of hydrogen based on inlet density, when inlet temperature and pressure conditions are within the limits defined in Appendix B. The calculated fuel pump suction specific speed is 10,640, the estimated efficiency is 61.2%, and the calculated power requirement is 509 horsepower. The test head rise through the fuel pump is shown in Appendix B. These fuel pump requirements were determined by analysis of the cycle balance necessary for best engine operation. This pump configuration has been checked in both rig and engine tests to verify its ability to meet these requirements.

The fuel pump impellers are machined from AMS 4135 aluminum alloy, which has a 0.2% yield strength of 54,000 psi at room temperature. Calculated fuel pump impeller membrane stresses are shown in Appendix A. Calculated fuel pump housing deflections are less than 0.010 inch or approximately 20% of minimum impeller clearances.

2. Oxidizer Pump

The oxidizer pump has a single-stage, fully shrouded impeller. This fully shrouded design allows larger clearances between the impeller and housing, which essentially eliminates the possibility of impeller rub. A complete oxidizer impeller and shroud are shown in figure I-11. The pump has a collecting volute and a straight conical diffuser for recovery of the velocity head. The impeller has radial vanes on the rear shroud. Thrust is 275 ± 50 lb in the aft direction which is carried by the thrust bearing. A three-bladed, axial-flow, fully shrouded inducer (figure I-12) increases impeller inlet pressure above vehicle supply pressure to prevent impeller cavitation. The inducer shroud incorporates a labyrinth seal to minimize leakage.

The oxidizer pump was designed to operate at 12,000 rpm with a minimum net positive suction head of 30.3 feet of liquid oxygen. The present operating point for the pump is 11,350 rpm and will provide a minimum weight flow of 29.3 lb/sec with a head rise of 877 feet of oxygen based on inlet density, when inlet temperature and pressure conditions are within the limits defined in Appendix B. The calculated oxidizer pump suction specific speed is 11,910, the estimated efficiency is 67%, and the calculated power requirement is 78.2 horsepower. Predicted oxidizer pump performance and calculated head rise are shown in Appendix B.

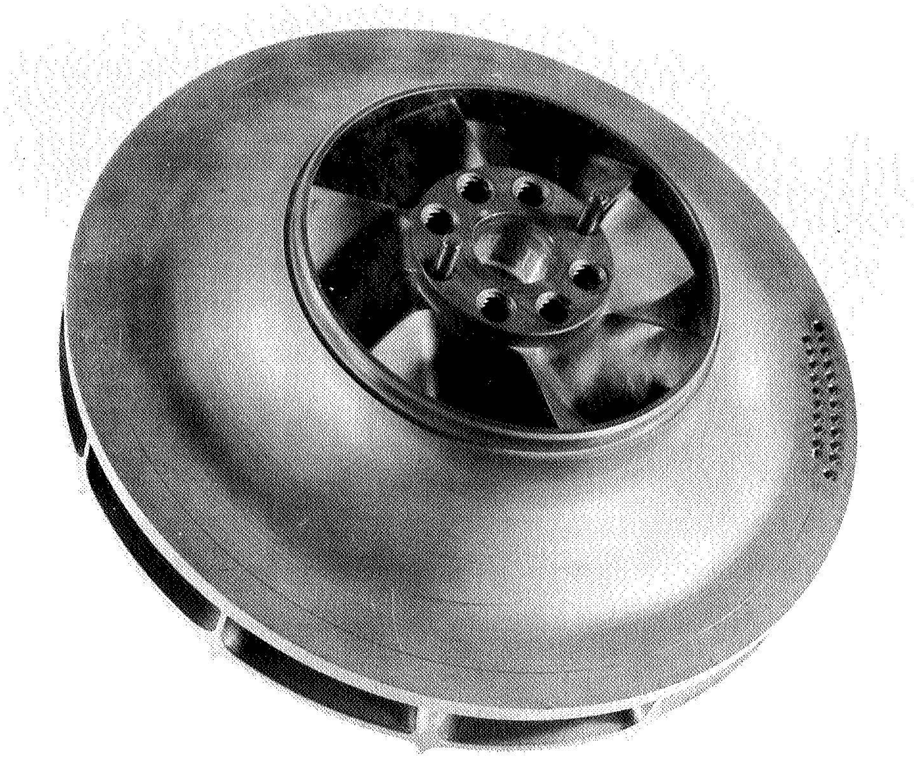


Figure I-11. Oxidizer Pump Shrouded Impeller FE 39351

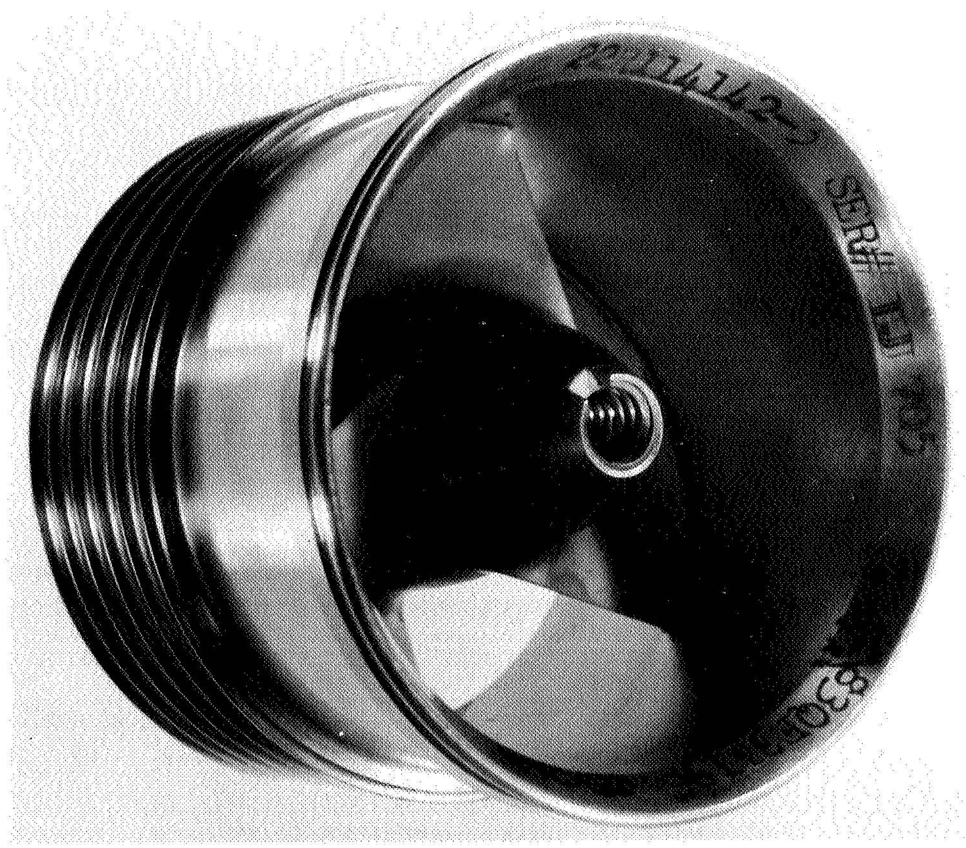


Figure I-12. Oxidizer Pump Shrouded Inducer FE 39352

3. Turbine

The turbine is a two-stage, partial-admission, impulse type. Both blade stages are manufactured in a single rotor and are fully shrouded to minimize blade tip leakage. Photographs of the turbine rotor before and after shroud installation are shown in figures I-13 and I-14.

The turbine was designed to deliver 824 horsepower at 30,000 rpm. At the present operating point the turbine delivers 592 horsepower at 28,400 rpm with an inlet temperature of 331°R, a total inlet pressure of 649 psi, a discharge temperature of 312°R, and a discharge pressure of 436 psia. Most of the 213 psi pressure drop occurs in the turbine inlet nozzles.

The estimated turbine efficiency of 58.8% is shown in Appendix B. Flow of hydrogen gas through the turbine at rated steady-state conditions is approximately 95% of the total hydrogen flow through the engine. The remaining fuel is bypassed by the thrust control.

The calculated turbine rotor stresses at 30,000 rpm as shown in Appendix A, are below the allowable stresses for the AMS 4127 aluminum material. A conical web between the rim and bore bends to absorb rim growth, which minimizes hub distortion to prevent unbalance. Vibration analysis of the turbine rotor indicates that the resonant frequencies are outside the maximum operating range.

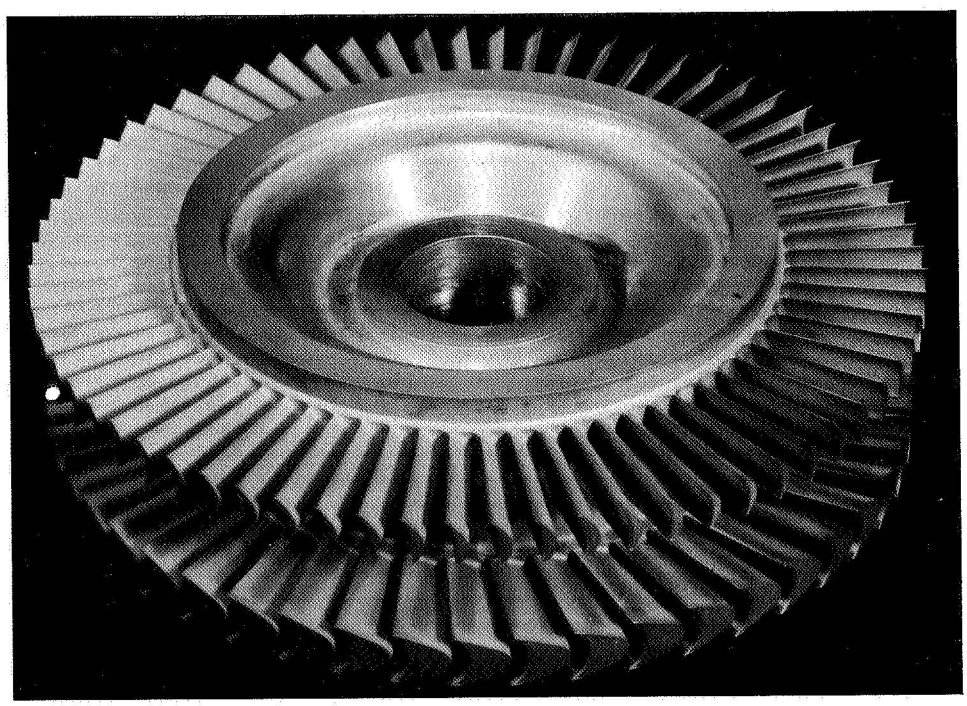


Figure I-13. Turbine Rotor Without Shroud FE 3973

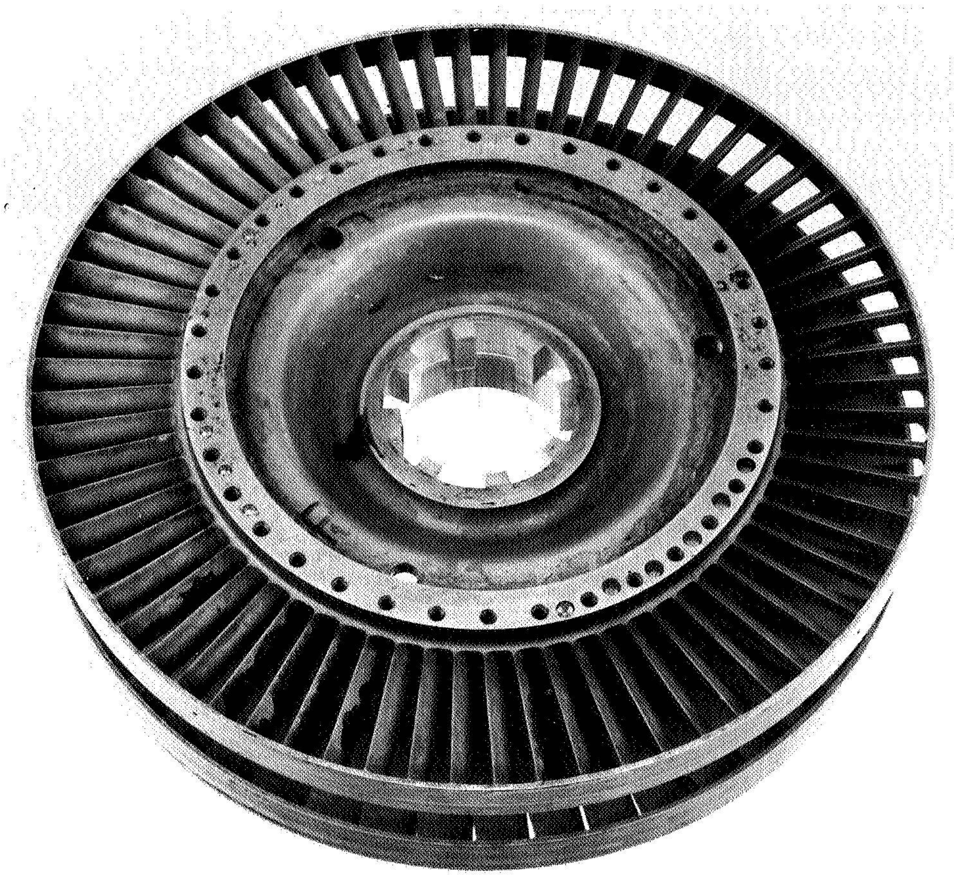


Figure I-14. Turbine Rotor with Shroud After Running FE 9530

4. Turbopump Drive System

The turbopump drive system consists of the bearings, seals, shafts, and gears in the turbopump housing. The main drive shaft, which transmits power to drive the fuel pump, also provides passages for hydrogen coolant flow to the ball bearing that supports the shaft at the turbine drive end. The supply of liquid hydrogen is bled from the 2nd-stage fuel pump inlet; the flow path is shown in figure I-15.

The ball bearing at the turbine drive end is preloaded by a spring washer that imposes an additional thrust load on the thrust bearing and ensures proper bearing loading. The fuel pump and turbine combined thrust load is transferred to the main pump housing by a ball thrust bearing.

Spur gears on the main drive shaft, idler shaft, and oxidizer pump shaft transmit the power drives to the oxidizer pump shaft. The gears are made of AMS 6260 material. Calculated load characteristics for the gears are shown in Appendix A. The oxidizer pump shaft gear also incorporates five lugs that provide the tachometer generator drive pickup points.

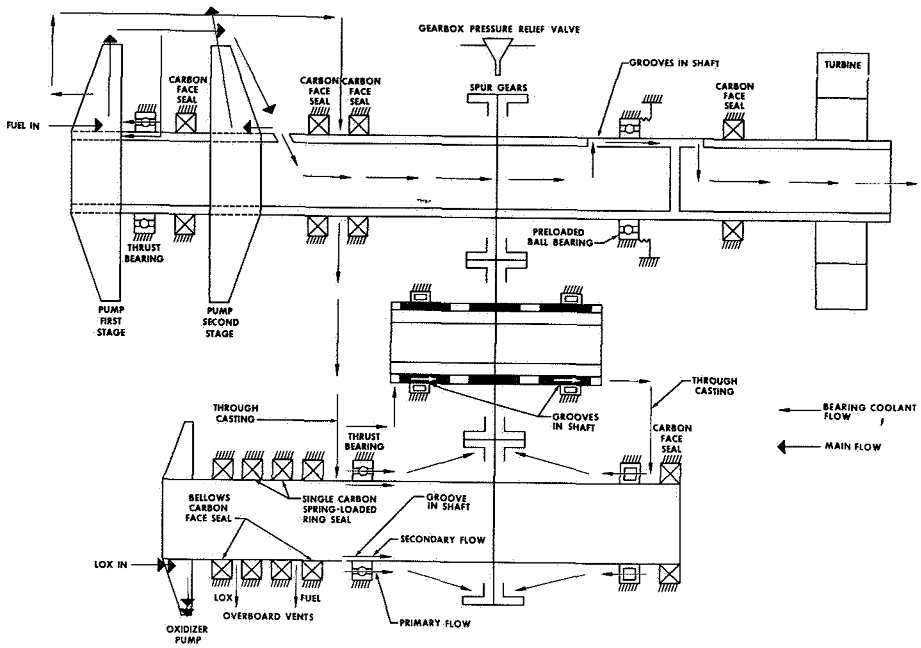


Figure I-15. Bearing Coolant Schematic FD 3167A

Liquid hydrogen coolant is supplied to the gearbox and oxidizer shaft from a plenum that is a cored passage in the fuel pump housing. The plenum is supplied by a transfer tube from the 1st-stage pump contour. The calculated flow rate required to cool the bearings and gears in the gearbox is 0.01 lb/sec, based on the heat generated due to the thrust load and friction of the bearings and gears operating at design load conditions.

The bearings and races of the turbopump assembly, which are made from consumable-electrode, vacuum-melted AMS 5630, were designed to operate under the following conditions:

1. Dry (no lubricant)
2. Temperature from 38°R to 158°R.

The following features are incorporated in the turbopump thrust bearings:

1. Split inner race ball bearings
2. Separator material of aluminum-armored plastic
3. Spin-roll ratio of 19%
4. Inner race riding cages.

Analysis of the fuel pump and oxidizer pump shafts showed calculated critical speeds of 44,000 rpm and 23,100 rpm, respectively. Vibration of the fuel pump is minimized by the dynamic balancing of the rotating parts. (Refer to Appendix A.)

The fuel pump interstage seal (figure I-16) consists of a single carbon-face type seal that was designed to limit leakage between pump stages to the flow that is required for interstage thrust bearing cooling. The carbon seal is supported against the rotating seal face by a retainer that is loaded by a spring washer. A metal seal ring in the retainer prevents leakage from bypassing the carbon seals.

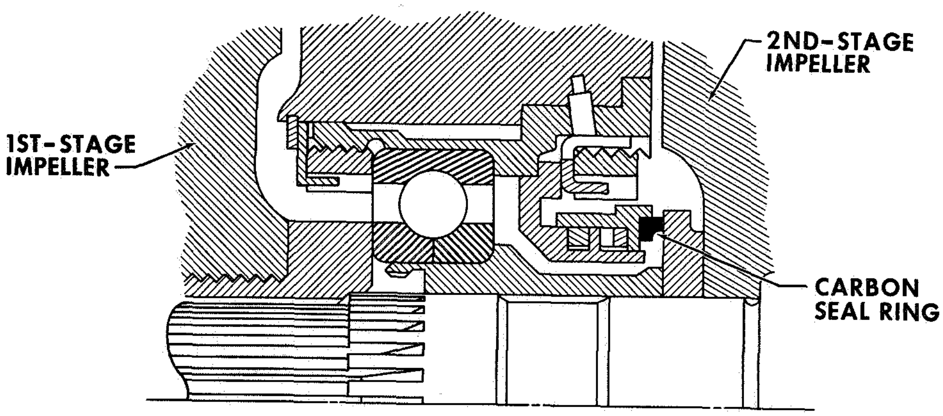


Figure I-16. Fuel Pump Interstage Seal FD 3150

The fuel pump face seal prevents leakage of fuel from the 2nd-stage pump inlet into the gearbox chamber. This seal (figure I-17) is a two-step configuration that provides the plenum for 1st-stage contour intermediate pressure to exist between the two carbon seal rings. The intermediate pressure is used to cool the idler shaft and oxidizer pump shaft bearings. The carbon seal rings are supported at the rotating seal faces by retainers that are loaded by spring washers, as shown in figure I-17. A metal seal ring is provided in each retainer to prevent leakage from bypassing the carbon seal rings.

The turbine rotor seal shown in figure I-18 is a carbon-face type seal that was designed to minimize leakage from the turbine rotor housing to the gearbox chamber. The carbon seal is supported at the rotating seal face by a retainer that is loaded by a spring washer. A metal seal is provided between the seal retainer and the carbon seal housing to prevent carbon seal ring bypass leakage.

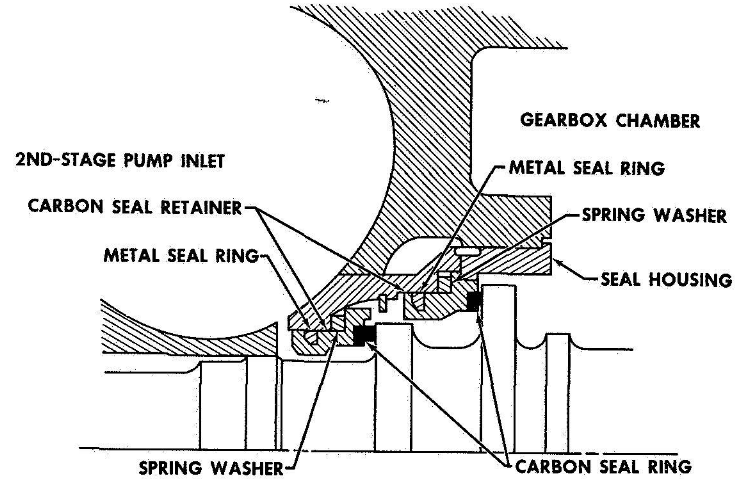


Figure I-17. Fuel Pump Face Seal FD 3148

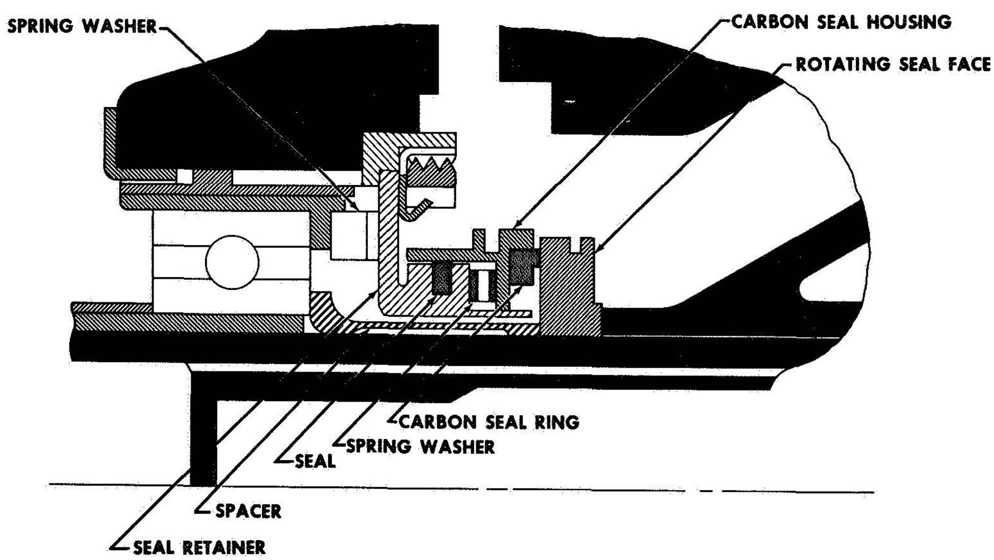


Figure I-18. Turbine Rotor Seal FD 3153

The oxidizer pump shaft seal, which is located between the oxidizer pump and gearbox, is shown in figure I-19. The seal consists of two bellows face type primary seals that minimize the leakage of fuel or oxidizer and provide overboard vents for any leakage flow that may result. The bellows is splined to a retainer that absorbs torque and provides damping but permits axial travel. Two carbon ring seals, which are positioned by spring washers, are used as a backup seal to prevent mixing of fluids in case of any one primary seal failure. The backup seal arrangement is also vented to an overboard connection. The accessory drive pad seal (figure I-20) is a bellows-type carbon-face seal that restricts the leakage of hydrogen coolant into the area between the turbopump and the drive spline.

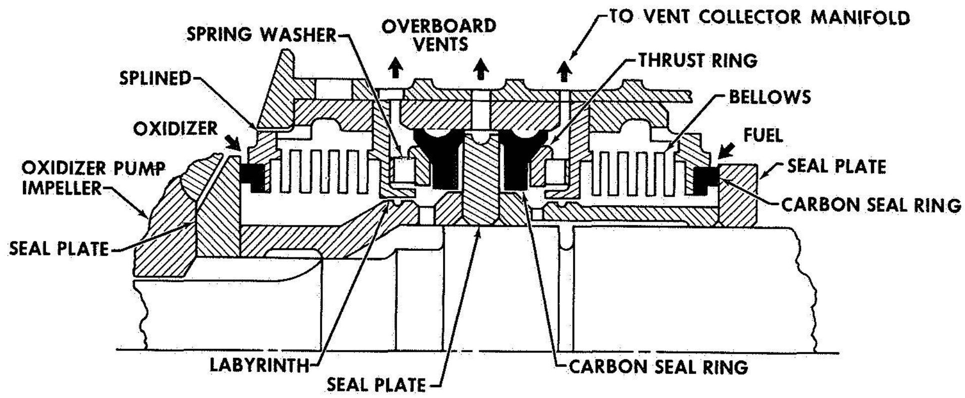


Figure I-19. Oxidizer Pump Seal FD 3151A

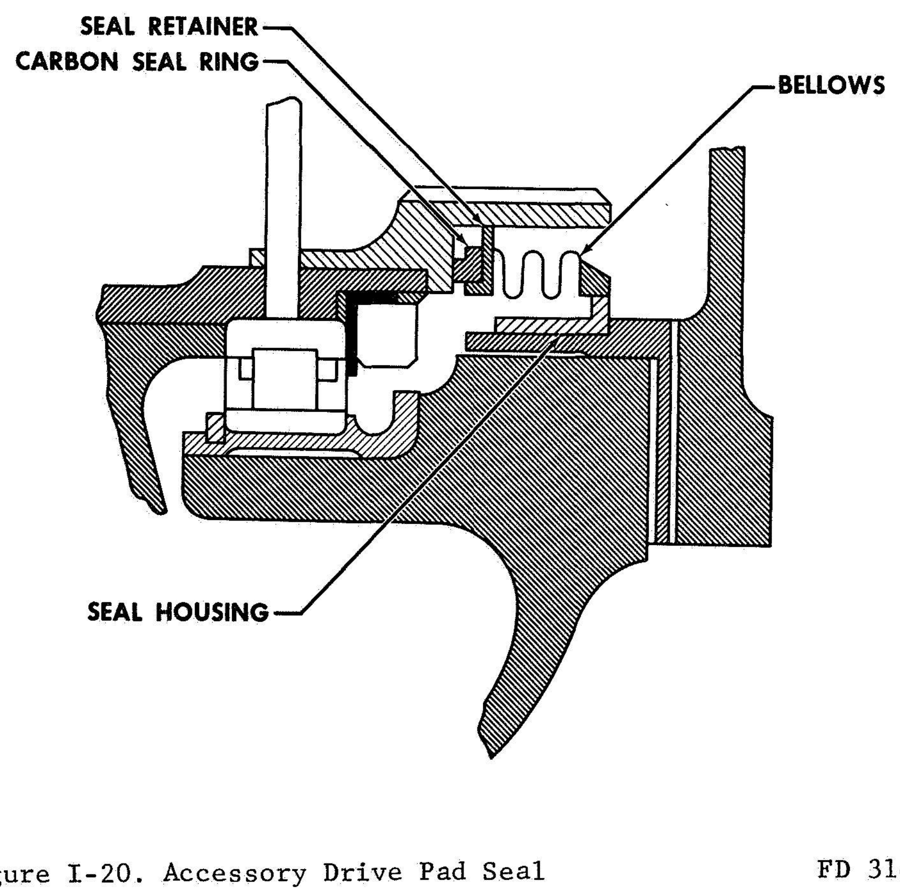


Figure I-20. Accessory Drive Pad Seal FD 3146

C. ACCESSORY DRIVE PAD

An accessory drive pad with gearbox torque check adapter is located on the aft end of the oxidizer pump shaft. The pad conforms to the latest issue of AND 20000. Specifications for its use are given in the RL10A-3-1 Liquid Rocket Engine Installation Handbook.

D. GEARBOX VENT AND PRESSURE RELIEF VALVE

The gearbox vent and pressure relief valve consists of a spring-operated poppet-type valve and a bypass bleed orifice. The valve serves to maintain gearbox pressure at 18 to 25 psi above ambient pressure. The bypass bleed orifice provides a vent during purging. The valve is mounted on the fuel pump drive gearbox housing.

E. THRUST CHAMBER

The thrust chamber is a brazed assembly that consists of an inlet manifold, 180 short single-tapered tubes, turnaround or rear manifold, 180 full-length double-tapered tubes, exit or front manifold, external stiffeners, and structural members for support of engine equipment. The full-length tubes lead axially rearward from the exit manifold and form the full periphery of the combustion chamber, throat, and forward part of the expansion chamber. The short tubes lead rearward from the inlet manifold and interleave between the full-length tubes to form the remainder of the expansion chamber. The turnaround manifold at the aft end of the expansion nozzle transfers coolant from the short tubes to the full-length tubes. The fuel, which acts as the coolant, flows rearward from the inlet manifold through the short tubes into the turnaround manifold, and through the full-length tubes to the exit manifold. Figure I-21 shows examples of the full-length double-tapered and short single-tapered tubes. The brazed joints between the tubes serve mainly as a seal because the chamber hoop loads are carried by the reinforcing bands. These bands also minimize the effect of any flow-induced vibration. Calculated stresses for various locations considered to be most critical are shown on a cross section of the thrust chamber in Appendix A.

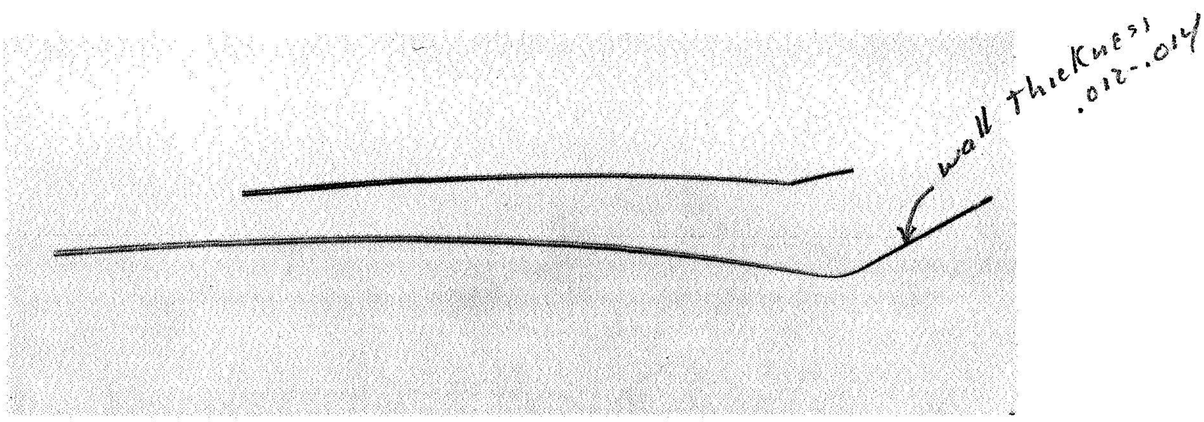


Figure I-21. Full-Length Double-Tapered Tube and Short Single-Tapered Tube   FE 3143

The fuel passing through the thrust chamber tubes must cool the tubes to maintain their structural soundness, and in doing this the fuel receives enough heat to supply turbine power for propellant pumping. The partial two-pass method of chamber construction was adopted as a means of achieving higher coolant velocity at the exit end of the thrust chamber, thereby increasing the heat transfer to fuel and reducing tube wall temperature. The pressure drop through the thrust chamber is 150.5 psi and the temperature rise is 280°R. This heat input is sufficient to operate the turbine at the design point with approximately 5% of the fuel bypassing the turbine.

At design conditions, the combustion chamber pressure is 300 psia with a nominal oxidizer-fuel mixture ratio of 5 to 1 by weight, a combustion chamber gas temperature of 5904°R, and a total propellant flow of 34.8 pounds per second. The combustion chamber has an L* (chamber volume divided by throat area) of 31.6 inches. The C* combustion efficiency, or characteristic exit velocity efficiency is estimated at 97.3%. The thrust chamber has an expansion ratio of 40 to 1, and the estimated specific impulse is 433 seconds at the design point mixture ratio. Estimated variation of specific impulse with mixture ratio is shown in Appendix D.

Design of the thrust chamber took into consideration the relationship of tube stresses, tube plastic strain, chamber hoop stresses, and vibration. Individual tube stresses in the hoop plane of the chamber that are caused by internal pressure are uniformly low (below 13,000 psi). Thrust chamber tube temperatures and pressures are plotted in Appendix D. Stresses in the axial plane resulting from the temperature gradients across the nozzle wall are in the plastic range in some locations, but are well below the ultimate strength of the material due to the nature of the loading.

The nozzle contour is based on a method of characteristics solution for ideal expansion that minimizes the formation of strong shock waves. The nozzle is truncated to provide an appreciable decrease in weight with little effect on thrust or specific impulse. The decrease in friction losses with the truncated design is more advantageous than the theoretical thrust increase resulting from using an ideal nozzle length.

F. PROPELLANT INJECTOR

The propellant injector atomizes and promotes mixing of the fuel and oxidizer to provide the correct conditions for ignition and efficient combustion.

The propellant injector consists of 216 elements arranged in 8 equally spaced concentric circles. Each element consists of a liquid oxygen nozzle and a concentric fuel annulus. All oxygen nozzles, except those in the inner and outer rows, incorporate swirlers (spiral deflectors). The design incorporates left-hand and right-hand swirlers that are alternately spaced in each of the six rows of nozzles.

The propellant discharge from the concentric orifices is normal to the injector surface. The concentric jet design with oxidizer swirlers brings the fuel and oxidizer into immediate contact when they leave the rear face of the injector. This design shortens the required mixing time, minimizes combustion instability, improves combustion efficiency, and improves engine specific impulse.

The oxidizer and fuel orifices are supplied from two separate chambers that are formed by the assembly of three mutually supported conical plates. Liquid oxidizer is supplied to the forward chamber through a central manifold. Machined tubes projecting from the center plate form the oxidizer orifices. The tubes extend through holes in the rear plate thus forming annular fuel orifices as shown in figure I-22. The rear plate is formed of porous welded steel mesh to provide transpiration cooling of the injector face, which totals 0.56 lb/sec or 10.4% of the total fuel flow. The calculated steady-state average temperature of the porous injector rear faceplate, as a function of the present total fuel flow passing through this plate, is shown in Appendix D.

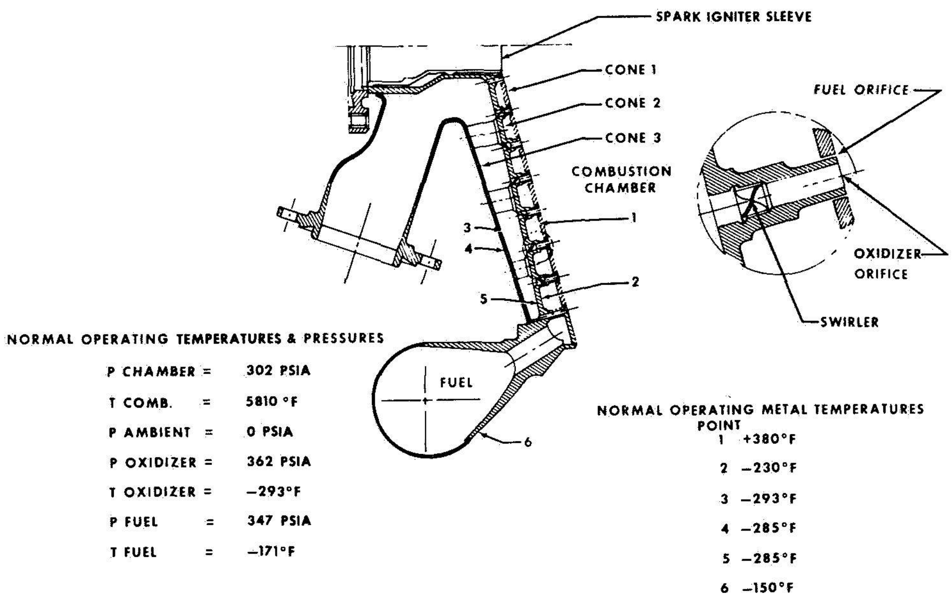


Figure I-22. Propellant Injector FD 1554B

Figure I-22 is a detail cross section of the injector showing the tabulated normal operating temperature and pressure conditions of the propellant injector head. The maximum bending stress calculated for the three cones and the fuel inlet manifold is 70,000 psi. Additional stress data are given in Appendix A.

G. PROPELLANT PIPING

The main propellant piping system is composed of the following five lines on the engine:

1. Oxidizer pump to injector tube
2. 1st-stage fuel pump discharge to 2nd-stage fuel pump inlet tube
3. Fuel pump discharge to thrust chamber

    a. Fuel pump to cooldown valve
    b. Cooldown valve to thrust chamber

4. Thrust chamber outlet to turbine inlet tube
5. Turbine discharge to injector inlet tube.

The main propellant system uses rigid lines to withstand fluid pressure loads and to carry support loads between flanges. The use of AISI 347 steel was dictated by elongation properties at cryogenic conditions and ease of fabricating high quality welded joints. Because of indeterminate installation loads as a result of tolerance accumulation and thermal loads, wall thickness of each manifold is based upon 1.4 times the maximum transient pressure, with hoop stresses established conservatively low to allow for all other loads.

All piping connections except the chamber inlet flange are sealed with radial-loaded Teflon-plated conical aluminum angle gasket seals, as shown in figure I-23. The chamber inlet connection is sealed with a similar seal design, except that an uncoated stainless steel gasket is used. Tolerance control on piping is held closely to maintain alignment required for angle gasket seal joints. The angle gasket seal is used because of its ability to seal gaseous fluids and withstand long-term storage.

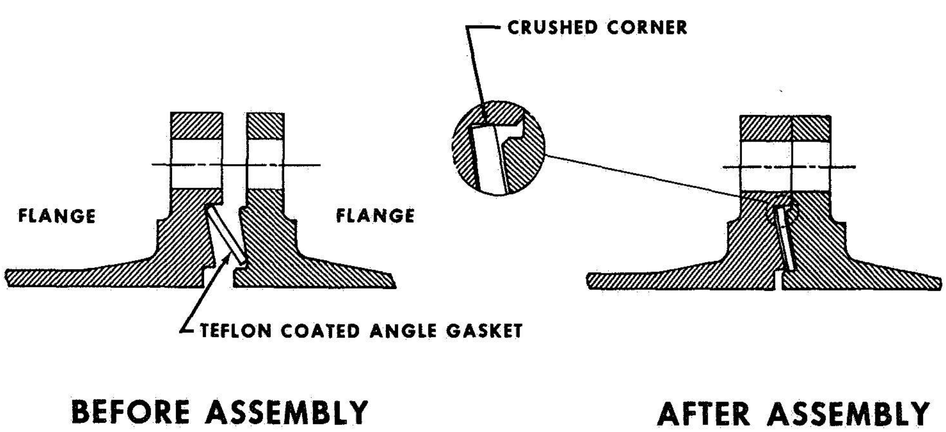


Figure I-23. Propellant Pipe Sealing Method FD 1557

H. ENGINE PLUMBING

Small lines on the engine, which are made from AMS 5571 tubing, are designed to withstand internal pressures, vibration, and installation loads. Length between support centers is adjusted using Specification MIL-P-5518B as a guide.

Small line connections and sealing is accomplished by the use of ferrules that are brazed to the tube. AN type fittings with 37.5-degree cone angle are used with a Teflon-coated aluminum flat gasket for sealing on bosses as shown in figure I-24.

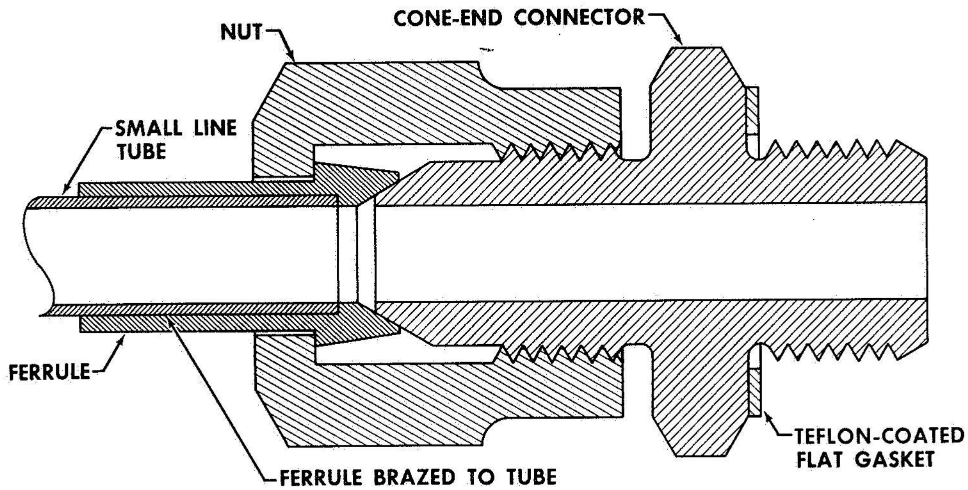
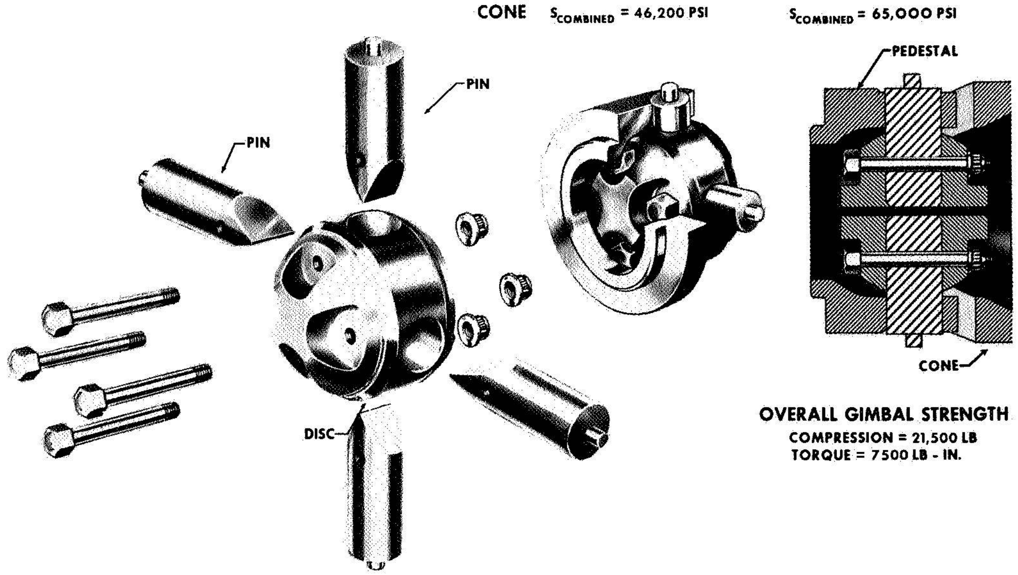


Figure I-24. Small Line Sealing Method FD 3166A

I. ENGINE MOUNT SYSTEM

The engine is attached to the vehicle by means of a gimbal mount assembly that consists of an aluminum pedestal, steel (lubricant coated) gimbal pins, a steel (lubricant coated) disc, and a conical aluminum engine mount. The gimbal assembly is shown in figure I-25.

	MAXIMUM STRESSES	ALLOWABLE STRESSES
PINS	$S_{BENDING}$ = 64,500 PSI	$S_{BENDING}$ = 85,000 PSI (0.2% YIELD)
DISC	$S_{BENDING}$ = 15,900 PSI	$S_{BENDING}$ = 85,000 PSI
CONE	$S_{COMBINED}$ = 46,200 PSI	$S_{COMBINED}$ = 65,000 PSI



OVERALL GIMBAL STRENGTH
COMPRESSION = 21,500 LB
TORQUE = 7500 LB - IN.

Figure I-25. Gimbal Assembly FD 1547C

The steel pins and disc that connect the pedestal to the conical mount allow a universal gimbaling action. These parts allow the engine to gimbal in a minimum square pattern of ± 4 degrees.

The mount is secured to the engine by six bolts that pass through the bottom of the conical mount and thread into the propellant injector. Four holes are provided in the pedestal for attachment to the vehicle.

Two lugs are located below the throat of the engine on the thrust chamber inlet manifold for attachment of vehicle thrust vectoring actuators. Appendix A gives the stresses in these attachments. The calculated maximum stresses and the allowable stresses for the gimbal mount are shown in figure I-25.

J. ELECTRICAL REQUIREMENTS

The RL10A-3-1 engine requires 28 volts dc electrical power for prestart and start solenoid valve operation and engine ignition. Steady-state voltage is 20 to 30 volts dc. Specific power requirements are as follows:

1. Ignition System — 2.5 amperes at 28 volts dc for a minimum of 2 seconds during each engine starting cycle.

2. Fuel prestart, oxidizer prestart, and start solenoid valves -- 2.0 amperes at 28 volts dc for each valve.

K. IGNITION SYSTEM

1. General

The ignition system consists of a spark igniter; a rigid, radio-shielded, high-tension lead; and an exciter assembly. At the beginning of the start cycle, which follows the prestart (cooldown) cycle, the vehicle supplies power to the spark igniter for approximately 2.0 seconds. The exact length of time is governed by vehicle programing and is independent of the actual time required for combustion to begin in the thrust chamber. The exciter releases a capacitance discharge to a high voltage spark igniter that is installed in the propellant injector of the engine. The exciter furnishes a minimum of 20 sparks per second at a nominal stored energy level of 0.5 joule per spark.

The exciter assembly and high-tension lead are hermetically sealed and internally pressurized to 20 to 30 psia to prevent electrical breakdown when operating under vacuum conditions. Epoxy coating is applied to the external surfaces and joints of the system to minimize the possibility of internal pressure loss.

Fuel and oxidizer are fed into the annulus surrounding the spark igniter (figure I-26). The annulus serves as a mixing chamber as the fluids flow toward the spark igniter tip. The spark igniter is recessed in the injector face to form a chamber that tends to keep the combustible mixture concentrated near the spark.

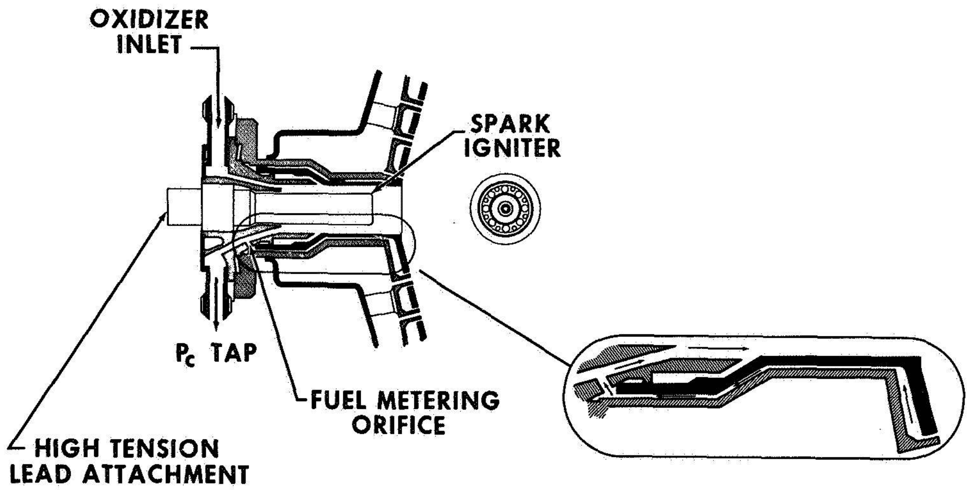


Figure I-26. Igniter Assembly FD 3134

The spark igniter electrode configuration prohibits the accumulation of moisture and provides many sharp corners to reduce and stabilize the breakdown voltage required.

2. Operational Theory

For this discussion, refer to figure I-27. Low voltage dc power, supplied to the two-pin input connector, passes from the connector through a radio noise filter. This internal filter circuit, which prevents high frequency feedback into the vehicle electrical system, is arranged to allow the use of a solid state switching device by the vehicle manufacturer. From the filter, the input current reaches the primary of a transformer that is an integral part of the vibrator. This current passes from the primary through a pair of normally closed contacts to ground. A breaker capacity (C4) is connected across these contacts to damp excessive arcing.

With the contacts closed, the flow of current through the coil produces a magnetic field. The magnetic force exerted by this field pulls the armature against the tension of the spring on which it is mounted. The movement of the armature causes the contact points to open, the flow of current stops, and the magnetic field collapses. The spring tension then returns the armature to its original position, closing the contacts, and the cycle recommences.

Each time the magnetic field collapses, it induces a high voltage in the secondary of the vibrator transformer. This produces successive pulses flowing through a gas-charged rectifier tube (V1) that limits the flow to a single direction and into the storage capacitor (C5). The storage capacitor (C5) accumulates an increasing charge at a constantly increasing voltage.

When this intermediate voltage reaches the predetermined level for which the sealed spark gap in the discharger tube (V2) has been calibrated, the gap breaks down. A portion of the accumulated charge on the storage capacitor follows a path through the primary of the indicating circuit transformer (T2), the primary of the triggering transformer (T1), the trigger capacitor (C6) to ground, and back through the discharger tube (V2) to the opposite side of the storage capacitor (C5).

This surge of current induces a voltage in the secondary of the trigger transformer (T1) sufficient to ionize the gap at the spark igniter and produce a trigger spark. The remainder of the accumulated energy on the storage capacitor is immediately discharged through the secondary of the trigger transformer and dissipated at the spark igniter. The path of flow in the discharge circuit is through the primary of the indicating circuit transformer (T2), the secondary of the triggering transformer (T1), the spark igniter to ground, and back through the discharger tube (V2) to the opposite side of the storage capacitor.

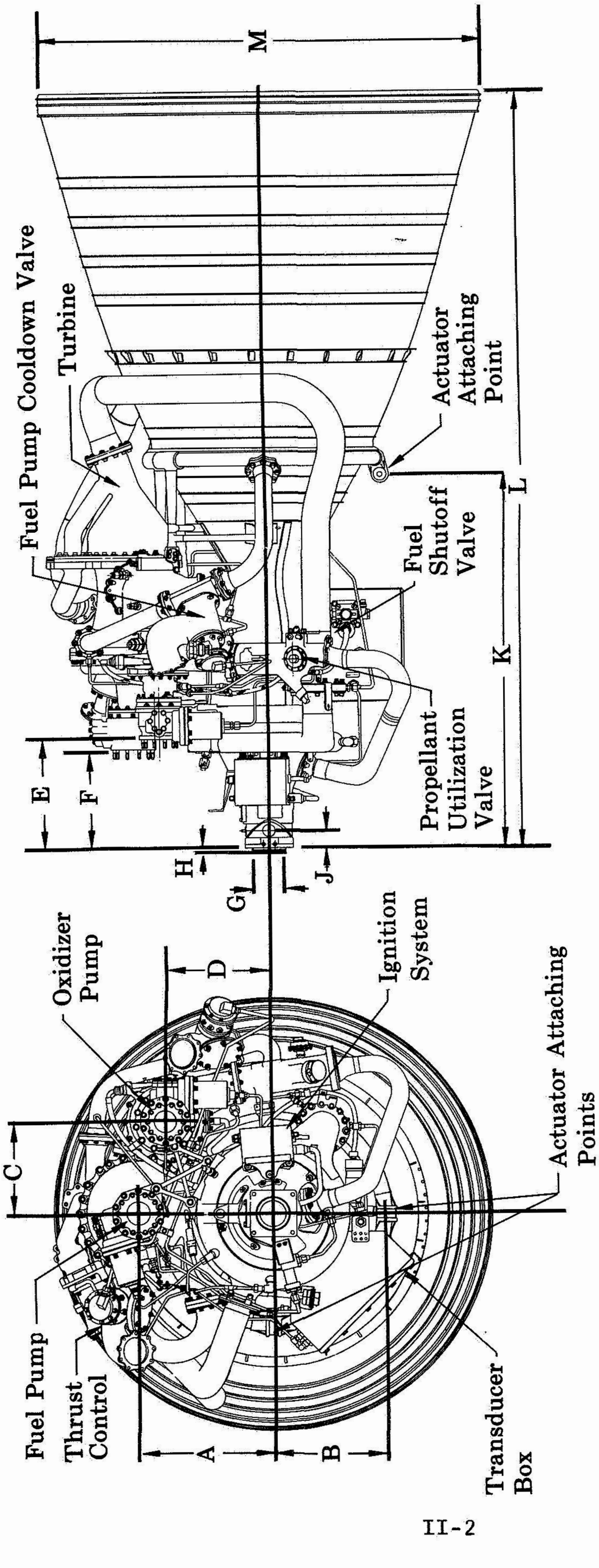
The bleeder resistor (R2) forms a part of the capacitor charging circuit and serves to dissipate the residual charge on the trigger capacitor between the completion of one discharge at the spark igniter and the beginning of the next cycle.

The spark rate will vary, depending on the value of the input voltage and the exciter temperature. At lower input voltage values, more time will be required to raise the intermediate voltage on the storage capacitor to the level necessary to break down the spark gap. However, since that level is established by the physical properties of the gap in the sealed discharger tube, a full store of energy will always be accumulated by the storage capacitor before discharge. At lower ambient temperatures, the copper losses in the circuit become less and the capacity of the storage capacitor is lowered, which causes the spark rate to increase.

A coupling transformer (T2) diverts a fraction of the discharging energy into the spark indicating circuit. The diodes, resistors, and capacitors of this circuit rectify these pulses to an approximate 6.5 volt dc signal. Connection of a suitable indicating device to the external two-pin connector provides a monitor of the ignition systems operation.

SECTION II
INSTALLATION DRAWING

The installation drawing of the RL10A-3-1 engine assembly is shown in figure II-1.



A — 11.750	D — 9.419	G — 2.876
B — 10.172	E — 9.603	H — 0.240
C — 8.128	F — 8.738	J — 1.500

K — 32.874	
L — 67.485	
M — 38.668	

Dimensions are Nominal in Inches at Room Temperature

FD 8895

Figure II-1. Engine Installation

SECTION III
ASSEMBLY DRAWING

The assembly drawing for the RL10A-3-1 engine assembly is shown in figure III-1.

FD 8896

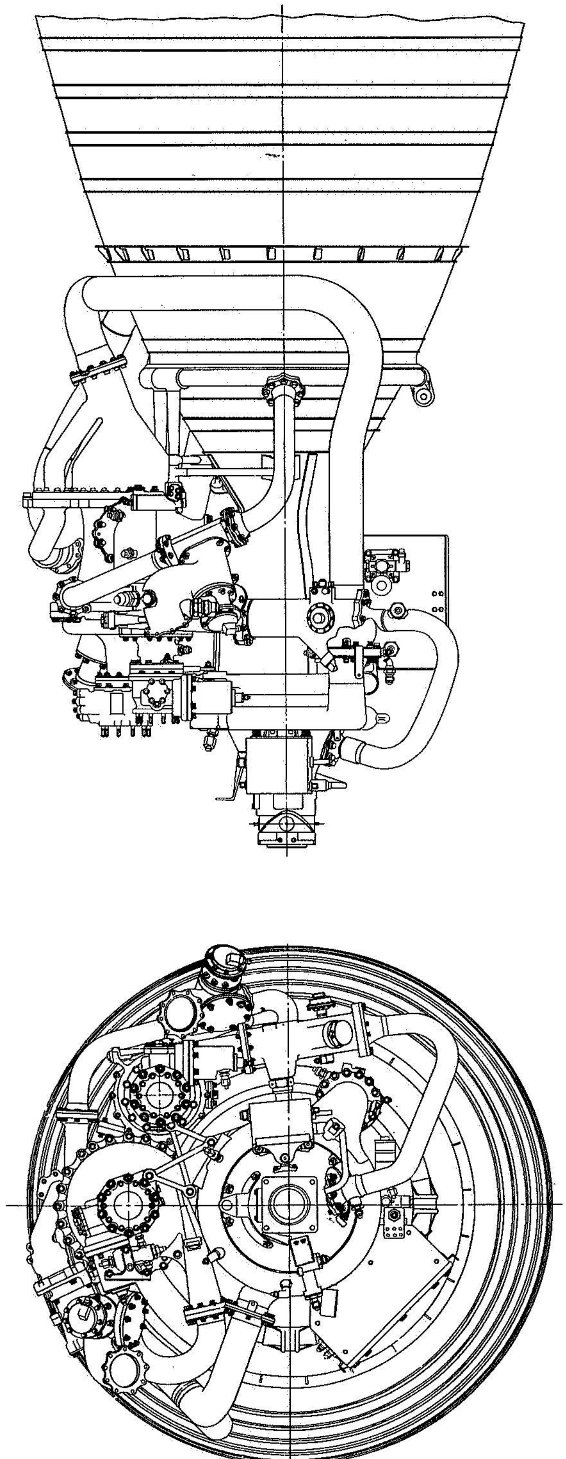


Figure III-1. RL10A-3-1 Engine Assembly

SECTION IV
WEIGHT BREAKDOWN

The weight breakdown of the RL10A-3-1 engine assembly is shown in table IV-1.

Table IV-1. RL10A-3-1 Assembly Weight Breakdown

Component	Weight, lb
Injector Assembly	13.88
Thrust Chamber	101.30
Turbopump	75.39
Turbopump Mounts	3.64
Engine Mount	11.15
Ignition System	6.30
Oxidizer Inlet Shutoff Valve	5.62
Fuel Inlet Shutoff Valve	5.89
Oxidizer Flow Control Valve	6.85
Fuel Cooldown Valve Interstage	8.20
Fuel Cooldown Valve Downstream	7.39
Thrust Control Valve	5.37
Main Fuel Shutoff Valve	4.21
Solenoid Valves	7.93
Oxidizer Flow Control Valve to Injector	2.56
Fuel Pump to Downstream Cooldown Valve	1.27
Downstream Cooldown Valve to Thrust Chamber	1.50
Thrust Chamber to Turbine	6.45
Turbine to Main Fuel Shutoff Valve	6.16
Small Lines	2.81
Connecting and Miscellaneous Hardware	6.97
TOTAL CHARGEABLE WEIGHTS	290.84
Instrumentation	13.30
Hydraulic Line Brackets	1.92
TOTAL ENGINE WEIGHT	306.06

SECTION V
ANALYSIS OF STEADY-STATE AND TRANSIENT PERFORMANCE

A. STEADY-STATE PERFORMANCE

The steady-state performance characteristics of the RL10A-3-1 engine are given in table V-1.

Table V-1. Estimated RL10A-3-1 Centaur Engine Design Data

Parameter	Ratings		
Mixture ratio	4.4	5.0	5.6
Altitude, ft	200,000	200,000	200,000
Thrust, lb	14,689	15,000	15,253
Nominal specific impulse, sec	436.8	433.0	427.6
Fuel flow, lb/sec	6.23	5.77	5.40
Oxidizer flow, lb/sec	27.40	28.86	30.27
Chamber pressure (throat total), psia	289.1	291.6	293.1
Chamber pressure (injector face static), psia	298.9	301.8	303.5
Oxidizer Pump			
Inlet pressure (total), psia	59.8	59.8	59.8
Inlet temperature, °R	176.6	176.6	176.6
Inlet density, lb/ft^3	69.0	69.0	69.0
Flow rate, gpm	178.3	189.7	196.8
Head rise, ft	894	869	841
Speed, rpm	11,497	11,327	11,165
Efficiency, percent	59.8	59.5	58.9
Horsepower	74.4	76.5	78.4
Discharge pressure, psia	488	476	463
Specific speed	938	970	1003
Fuel Pump — Mixture Ratio	4.4	5.0	5.6
Inlet pressure (total), psia	38.4	38.4	38.4
Inlet temperature, °R	38.8	38.8	38.8
Inlet density, lb/ft^3	4.34	4.34	4.34
Discharge density, lb/ft^3	4.190	4.182	4.169
Flow rate	644.7	597.4	559.1
Fuel leakage, lb/sec	.09	.09	.09
Head rise, ft	30,888	30,222	29,583
Speed, rpm	28,742	28,317	27,912
Efficiency, percent	56.5	55.4	54.18
Horsepower	585	539	503
Discharge pressure, psia	949	926	903
Specific speed (per stage)	526	507	492

Turbine	Mixture Ratio 4.4	5.0	5.6
Inlet total pressure, psia	676	652	633
Inlet total temperature, °R	288.6	323.8	355.6
Discharge static pressure, psia	420	420	419
Downstream total pressure, psia	387	387	385
Speed, rpm	28,742	28,317	27,912
Efficiency, percent	58.7	58.8	58.7
Horsepower	664	620	586
Turbine flow, lb/sec	6.12	5.47	5.01
Percent bypass flow	0.17	3.61	5.62
Effective area, in^2	1.125	1.125	1.125
Thrust control bypass area, in^2	0.0019	0.0422	0.0669
Thrust Chamber Assembly			
Chamber pressure (injector static), psia	298.9	301.8	303.5
Chamber pressure, (throat total), psia	289.1	291.6	293.1
Fuel flow, lb/sec	6.14	5.68	5.31
Oxidizer flow, lb/sec	27.40	28.86	30.27
Chamber mixture ratio	4.46	5.08	5.70
C* efficiency, percent of shifting	98.9	98.5	98.0
C* (actual), ft/sec	7,810	7,640	7,460
Combustion temperature (ideal), °R	5,550	5,810	6,000
Gas constant (ideal), ft/°R	143.3	130.7	120.8
Specific heat ratio	1.216	1.210	1.206
C_s (thrust coefficient efficiency), percent	97.59	97.25	96.90
Characteristic length (L*), in.	31.6	31.6	31.6
Chamber area (injector end), in^2	83.4	83.4	83.4
Chamber throat area, in^2	28.1	28.1	28.1
Effective expansion ratio, A/A*	40.0	40.0	40.0
Pressure Drop Summary			
Fuel			
Pump pressure rise, psid	910	887	864
Downstream orifice, psid	92.9	80	70.2
Cooldown valve, psid	.39	.34	.29
Liquid line, psid	4.1	3.5	3.1
Jacket, psid	146.9	149.8	149.4
Gas line upstream venturi, psid	3.3	3.2	3.2
Venturi, psid	24.6	36.6	43.6
Turbine (total to static), psid	256	232	214
Turbine discharge casing (total to static), psid	33.6	33.6	33.5
Gas line, turbine discharge to main fuel shutoff valve, psid	16.2	15.8	15.2
Main fuel shutoff valve, psid	11.0	10.7	10.3
Injector, psid	60.3	58.4	56.3

Oxidizer			
Pump pressure rise, psid	428	416	403
Mixture ratio control valve, psid	139.5	117.4	94.8
Liquid line, psid	5.6	6.2	6.8
Injector, psid	44.0	50.6	57.5
Temperature Rise Summary			
Fuel			
Pump rise, °R	16.3	16.4	16.5
Jacket, °R	233.5	268.7	300.3
Turbine, °R	-19.9	-20.4	-21.1
Oxidizer			
Pump rise, °R	2.8	2.7	2.6

B. TRANSIENT PERFORMANCE

The transient performance characteristics of the RL10A-3-1 engine are shown in figures V-1 through V-3.

C. SEQUENCE OF ENGINE OPERATION

The design sequence of operation for the RL10A-3-1 engine is shown in figure V-4.

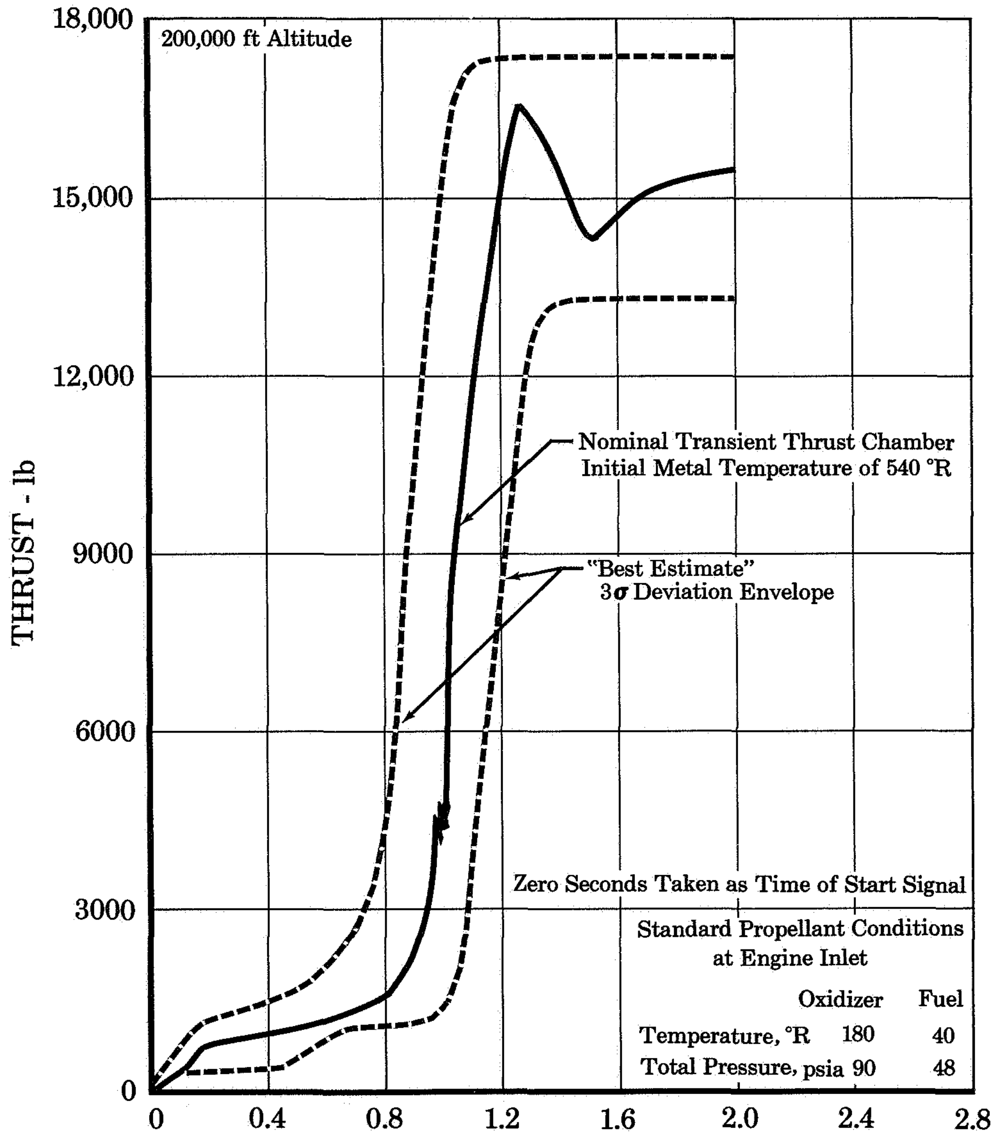


Figure V-1. Estimated Starting Transient Showing "Best Estimate" 3σ Deviation Envelope FD 8876

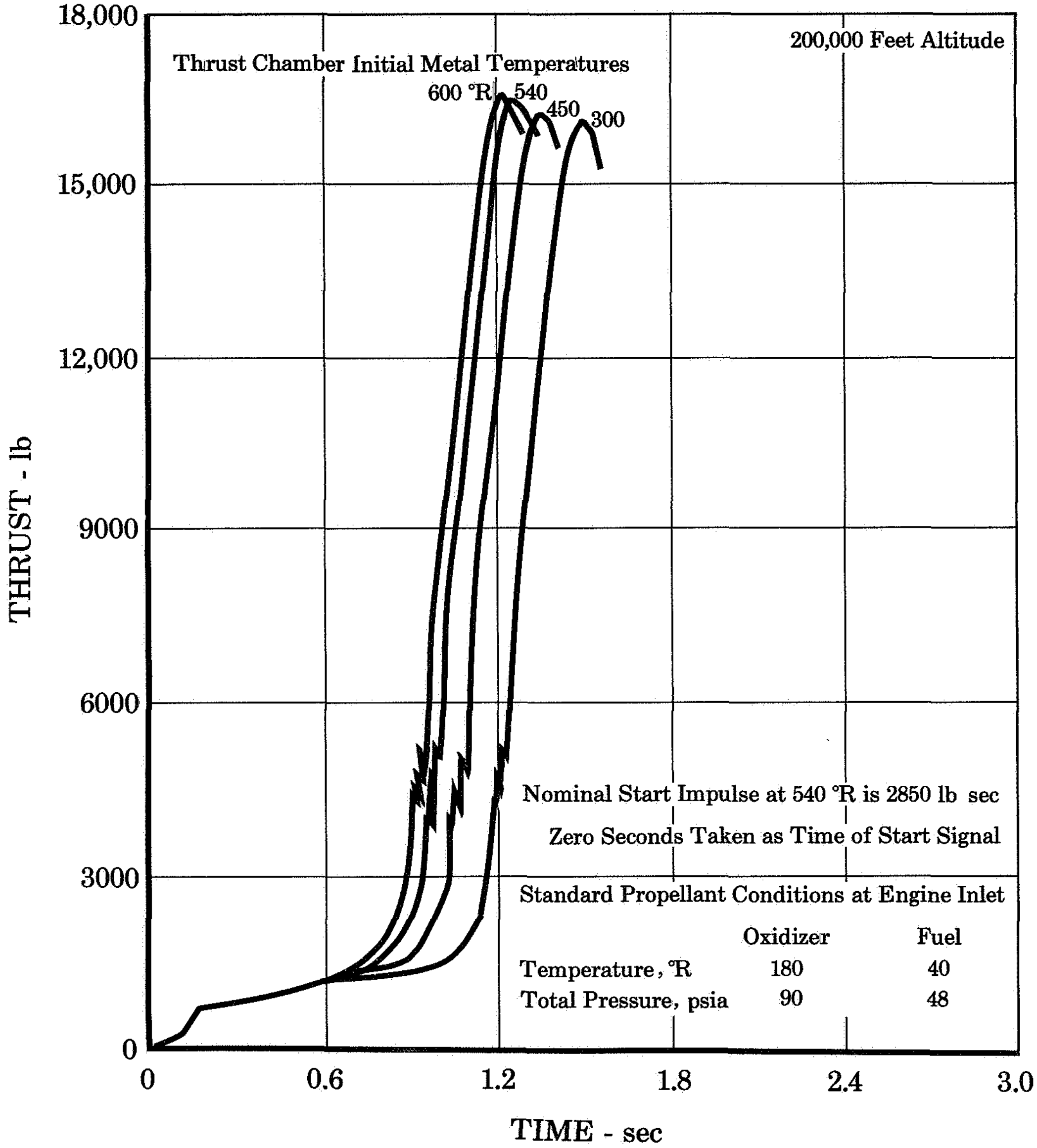


Figure V-2. Estimated Starting Transient Showing Effects of Initial Thrust Chamber Wall Temperatures FD 8877

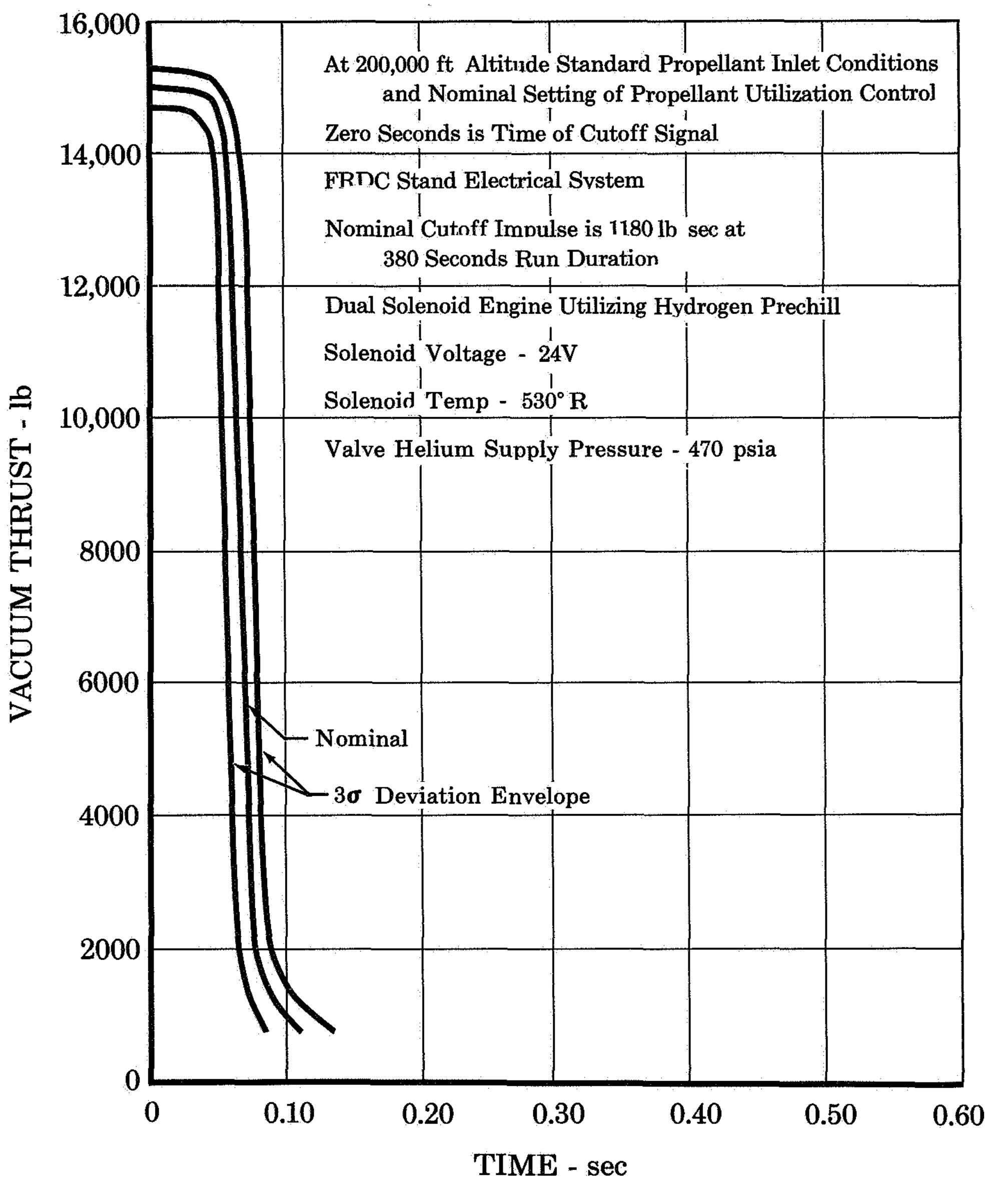


Figure V-3. Estimated Shutdown Transient Thrust vs Time FD 8878

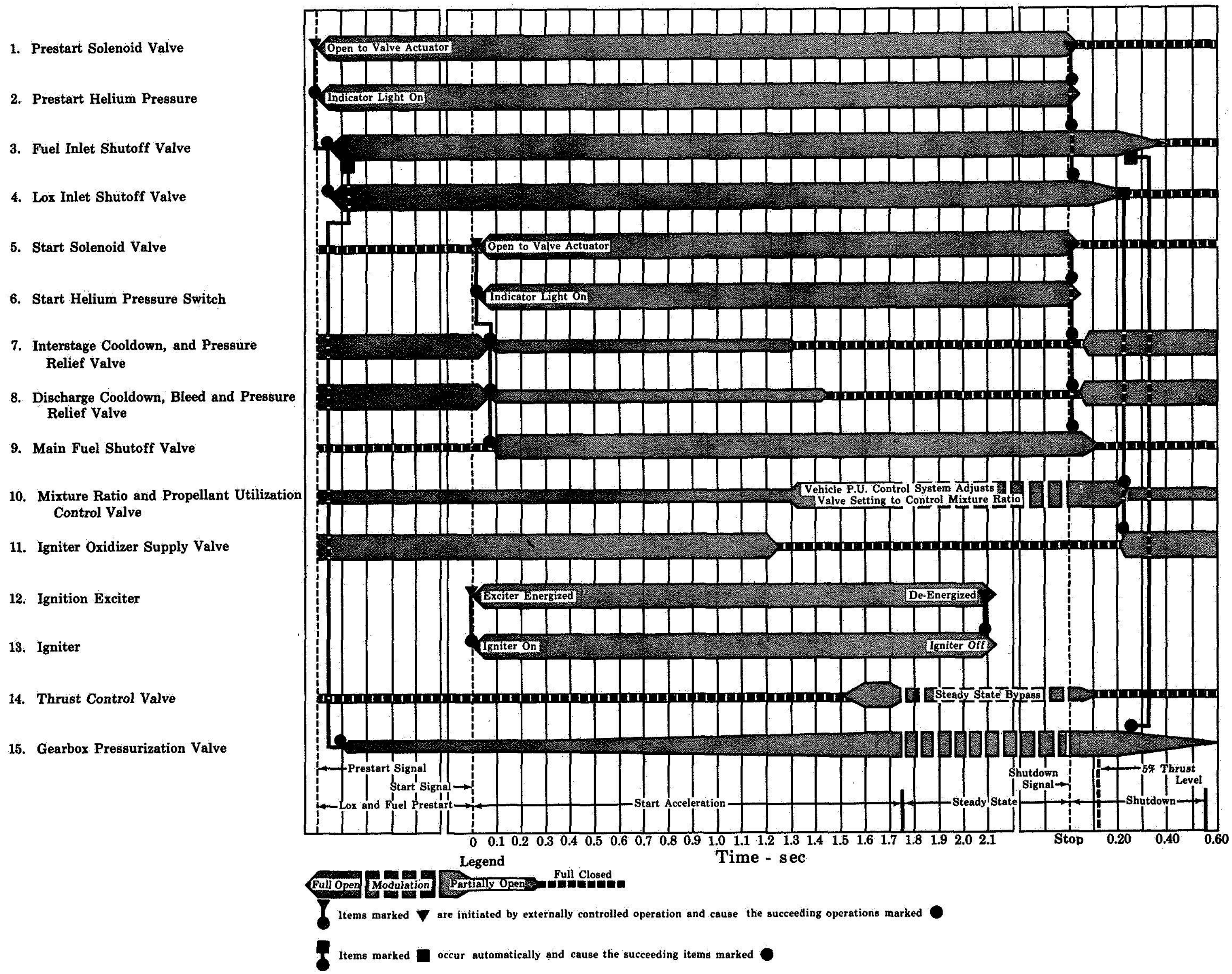


Figure V-4. Design Sequence of Engine Operation for RL10A-3-1

F 7369

SECTION VI
SCHEMATIC DRAWING

The propellant flow schematic for the RL10A-3-1 engine assembly is shown in figure VI-1.

FD 7368

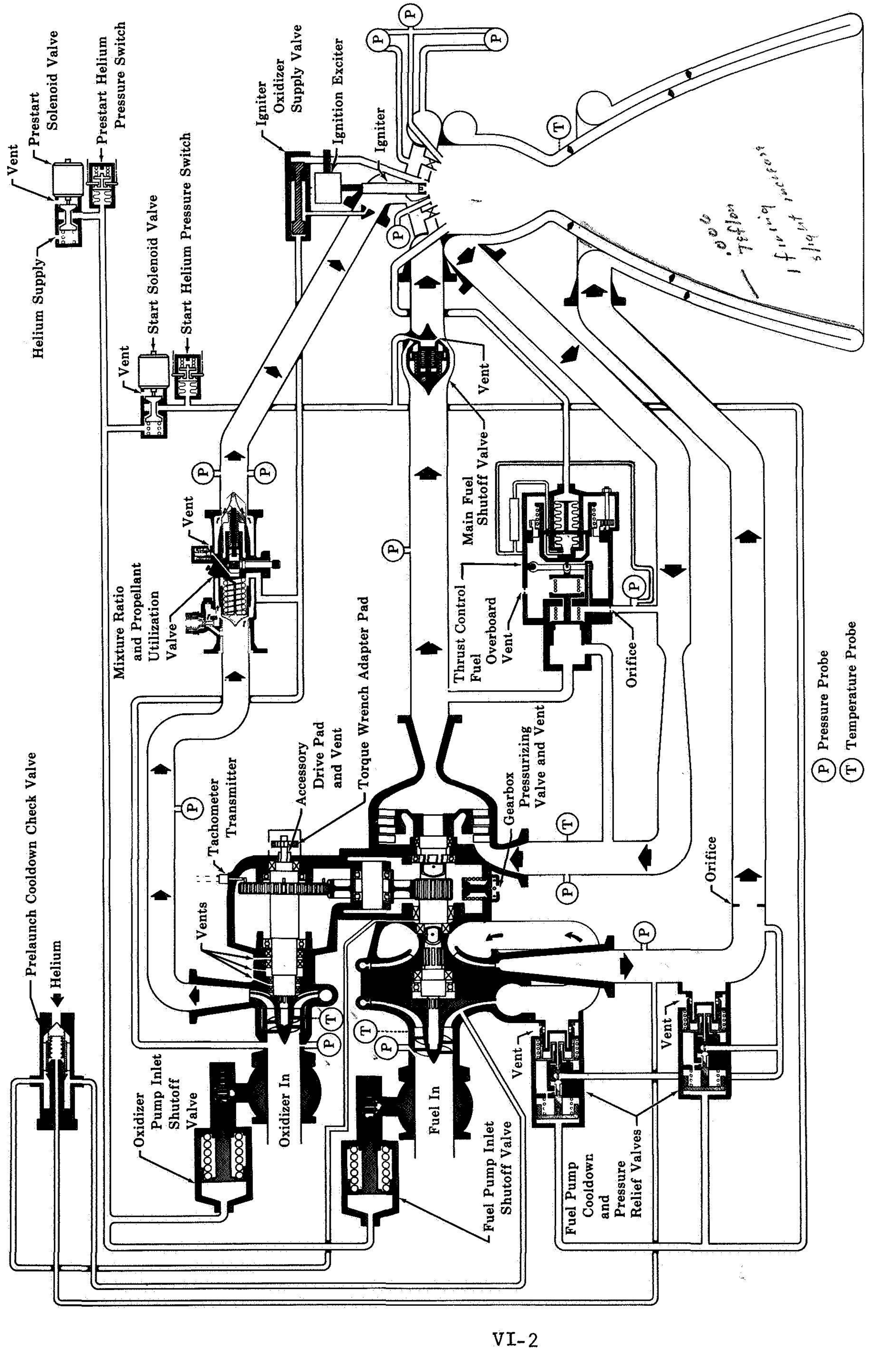


Figure VI-1. Propellant Flow Schematic for RL10A-3-1

SECTION VII
MATERIALS GLOSSARY

A. COMPONENT MATERIALS

The materials used in major engine components are listed in the following table.

Table VII-1. Materials Used in Major Engine Components

Component	Material	Type
Tubes	Stainless Steel Tubing	PWA 770 (AISI 347)
Exit Manifold		
Machined portion	Stainless steel forging	AMS 5646
Formed portion	Stainless steel sheet	AMS 5512
Reinforcing bands	Stainless steel sheet	AMS 5512
Porous injector face	Heat resistant alloy wire	AMS 5794
Gimbal pintles	High strength stainless steel bar	AMS 5735
Gimbal pedestal and cone	Aluminum alloy forgings	AMS 4139
Brackets	Stainless steel sheet	AMS 5512
Turbopump		
Housings	Aluminum alloy castings	AMS 4215
Fuel impellers	Aluminum alloy forgings	AMS 4135
Oxidizer impellers	Stainless steel forging	AMS 5646
Turbine blades	Aluminum alloy extrusion	AMS 4160
Shaft	High strength nickel alloy bar	AMS 5667
Gears	Carburizing steel	AMS 6260
Valves		
Housings		
Thrust control	Aluminum alloy casting	AMS 4215
Oxidizer flow control and pressure relief valve	Aluminum alloy forging	AMS 4127
Main fuel shutoff valve	Cast stainless steel	AMS 5362
Fuel inlet valve	Aluminum sand casting	AMS 4217
Solenoid valve	Stainless steel forging	AMS 5646
Prelaunch cooldown check valve	Stainless steel bar	AMS 5646
Gox valve	Stainless steel bar	AMS 5646
Cooldown valve	Aluminum bar	AMS 4117
Springs	Stainless steel wire	AMS 5688
Bellows	Stainless steel sheet	AMS 5512

Table VII-1. (Continued)

Component	Material	Type
Miscellaneous		
Fuel lines	Stainless steel tubing	AMS 5571
Gaskets	Plant fiber packing	PWA 470
Gasket	Plastic	AMS 3651
Gaskets	Aluminum sheet	AMS 4001
Gaskets	Aluminum sheet	AMS 4025
Plugs	Aluminum bar stock	AMS 4120
Flanges	Aluminum alloy forging	AMS 4127
Flanges	Stainless steel forging	AMS 5646
Cover	Aluminum alloy casting	AMS 4212
Gaskets	Copper sheet	AMS 4500
Spring washers	Copper beryllium sheet	AMS 4532
Washers and clips	Stainless steel sheet	AMS 5510
Bracket	High strength stainless steel sheet	AMS 5525
Tubes	Stainless steel tubing	AMS 5571
Rings and spacers	Stainless steel bar	AMS 5613
Bearings	Stainless steel bar and forging	AMS 5630
Valve housings and plugs	Free machining stainless steel bar	AMS 5640
Misc small parts	Stainless steel bar and forgings	AMS 5646
Nuts	Stainless steel bar and forgings	AMS 5735
Spacers, liners	High strength nickel alloy bar and forgings	AMS 5668
Safety wire	Nickel alloy wire	AMS 5685
Fasteners	High strength stainless steel bar	AMS 5735
Threaded inserts	Stainless steel wire	AMS 7245

SECTION VIII
ENGINE PARTS LIST

The RL10A-3-1 engine parts list is a part of this design report. The alphabetical parts list, P&WA Form No. PWA F-1351 A-F, is revised as engineering changes occur; the numerical parts list, P&WA Form No. PWA-1351-BF-1/61, is issued on a monthly basis. The current numerical parts list was issued 19 June 1964.

A current RL10A-3-1 engine parts list is not submitted in this report but copies are available at Pratt & Whitney Aircraft FRDC, and will be transmitted upon request.

SECTION IX
PROPELLANTS AND ANCILLARY FLUIDS
PRESSURE AND TEMPERATURE REQUIREMENTS

The estimated liquid hydrogen conditions required at fuel pump inlet are shown in figure IX-1. The estimated liquid oxygen conditions required at oxidizer pump inlet are shown in figure IX-2.

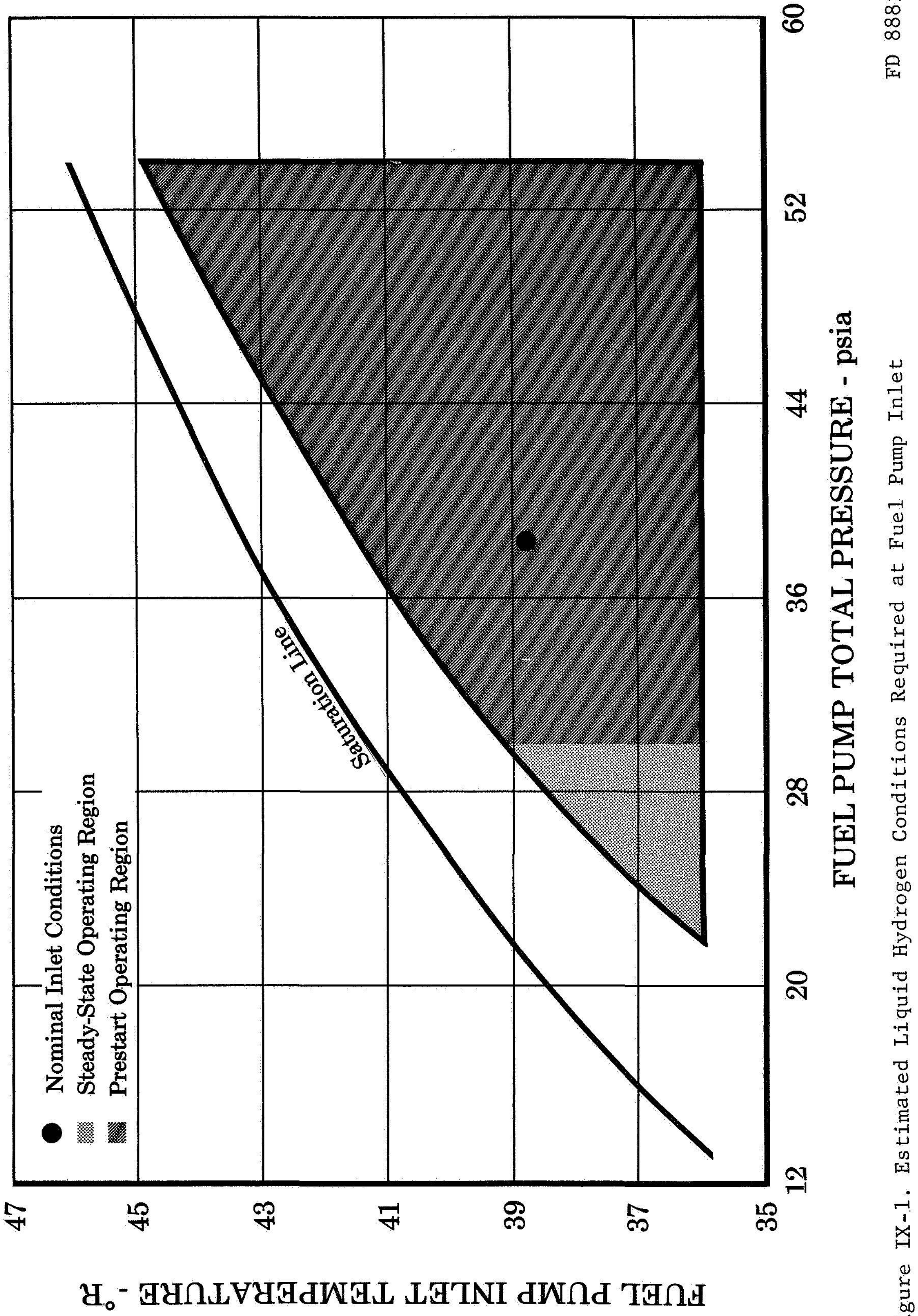
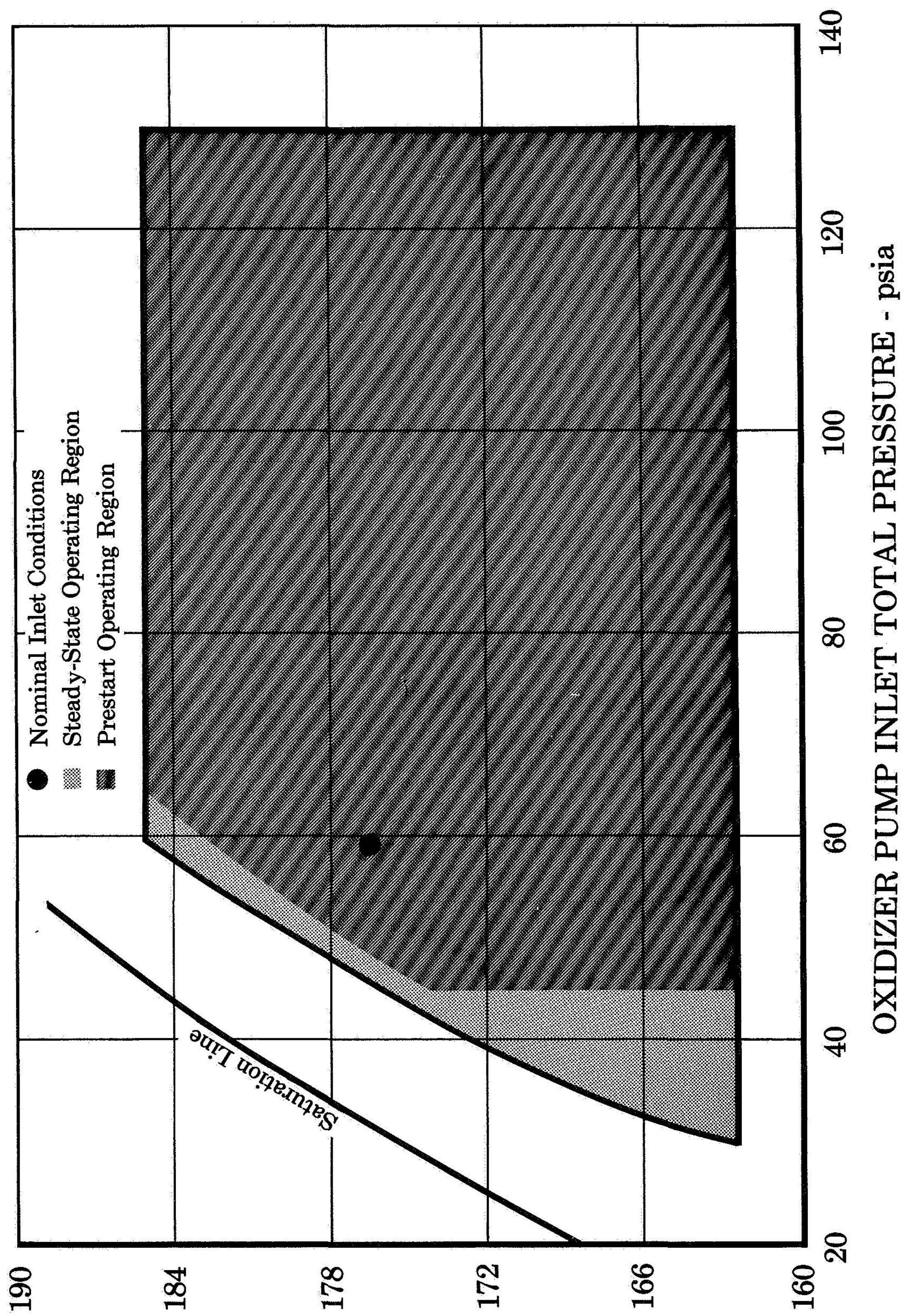


Figure IX-1. Estimated Liquid Hydrogen Conditions Required at Fuel Pump Inlet



FD 8883

Figure IX-2. Estimated Liquid Oxygen Conditions Required at Fuel Pump Inlet

SECTION X
MALFUNCTION ANALYSIS

A. GENERAL

The RL10A-3-1 engine was specifically designed to minimize the effects of possible propulsion system malfunctions on engine performance and durability. An investigation and analysis was made of these malfunctions and their effect on the RL10A-3-1 engine. Pratt & Whitney Aircraft Model Specification 2272D, Revision 2, requires an analysis of certain malfunctions when they occur during stable engine operation. The analysis was extended to investigate each malfunction for its effect if it had occurred at each phase of engine operation, as follows:

1. Prestart
2. Acceleration
3. Steady-state or stable engine operation
4. Shutdown.

Analysis of the following malfunctions is required by the Model Specification:

1. Failure of electrical supply to prestart solenoid
2. Failure of electrical supply to start solenoid
3. Failure of the engine electrical supply
4. Failure or shutoff of the helium supply
5. Failure or shutoff of the oxidizer supply
6. Failure or shutoff of the fuel supply.

This report also covers the following malfunctions that are not prescribed in the Model Specification:

1. Failure or shutoff of the igniter electrical supply
2. Electrical supply variations in excess of specification limits
3. Helium supply variations in excess of specification limits
4. Propellant inlet pressure and temperature outside specification limits
5. Ambient pressure and temperature outside specification limits
6. Failure of thrust control
7. Closing of main fuel shutoff valve.

It was assumed that the malfunction under discussion in each section occurs independently of any other malfunction.

B. RESULTS — MALFUNCTIONS REQUIRED BY MODEL SPECIFICATION 2272

1. Failure of Electrical Supply to Fuel Prestart Solenoid

a. Prestart

Engine returned to shutdown condition. No effect on subsequent operation if electrical supply is restored and adequate cooldown time is allowed.

b. Acceleration

Engine shutdown sequence will be normal but system response time will increase slightly. If the electrical supply is restored and the normal starting sequence is followed, the engine will be capable of normal operation.

c. Steady-State

Engine shutdown sequence will be normal, but system response time will increase slightly. If the electrical supply is restored and the normal starting sequence is followed, the engine will be capable of normal operation.

d. Shutdown

Normal for this phase. No effect on subsequent operation if electrical supply is restored.

2. Failure of Electrical Supply to Oxidizer Prestart Solenoid (Where Separate Solenoid Valve is Used)

a. Prestart

Engine returns to shutdown condition. No effect on subsequent operation if electrical supply is restored and adequate cooldown time allowed.

b. Acceleration

Turbopump speed will increase slightly prior to engine shutdown. If the electrical supply is restored and the normal starting sequence is followed, the engine will be capable of normal operation.

c. Steady-State

Turbopump speed will increase slightly prior to engine shutdown. If the electrical supply is restored and the normal starting sequence is followed, the engine will be capable of normal operation.

d. Shutdown

Normal for this phase. No effect on subsequent operation if electrical supply is restored.

3. Failure of Electrical Supply to Start Solenoid

a. Prestart

No effect. Normal for this phase of engine operation.

b. Acceleration

The main fuel shutoff valve will fail to open and fuel will be prevented from entering the combustion chamber. The engine will not start, but will remain in the prestart or cooldown phase with propellants lost overboard until the prestart signal is removed. If the electrical supply is restored, the engine will be capable of normal operation. The effect of a failure during the latter portion of the acceleration phase is similar to failure during the steady-state phase on a reduced scale. (Refer to paragraph 3c following.)

c. Steady-State

The engine will shut down in a normal manner, returning to the cooldown phase with propellants lost overboard until the prestart signal is removed. (See figure X-1.) If the electrical supply is restored and the normal starting sequence is followed, the engine will be capable of normal operation.

d. Shutdown

Normal for this phase. No effect on subsequent operation if electrical supply is restored.

4. Failure of the Engine Electrical Supply

a. Prestart

Engine remains shut down because the solenoid valves control the helium supply to the engine. No effect on subsequent operation if the electrical supply is restored.

b. Acceleration

Engine will remain shut down or will shut down normally. No effect on subsequent operation if electrical supply is restored and the normal starting sequence is followed.

c. Steady-State

The results are the same as described for the acceleration phase. (Refer to paragraph 4b, preceding.)

d. Shutdown

Normal for this phase. No effect on subsequent operation if electrical supply is restored.

5. Failure or Shutoff of the Helium Supply

a. Prestart

Inlet valves will remain closed and the engine will not cool down. If the helium supply is restored, the engine will be capable of normal operation.

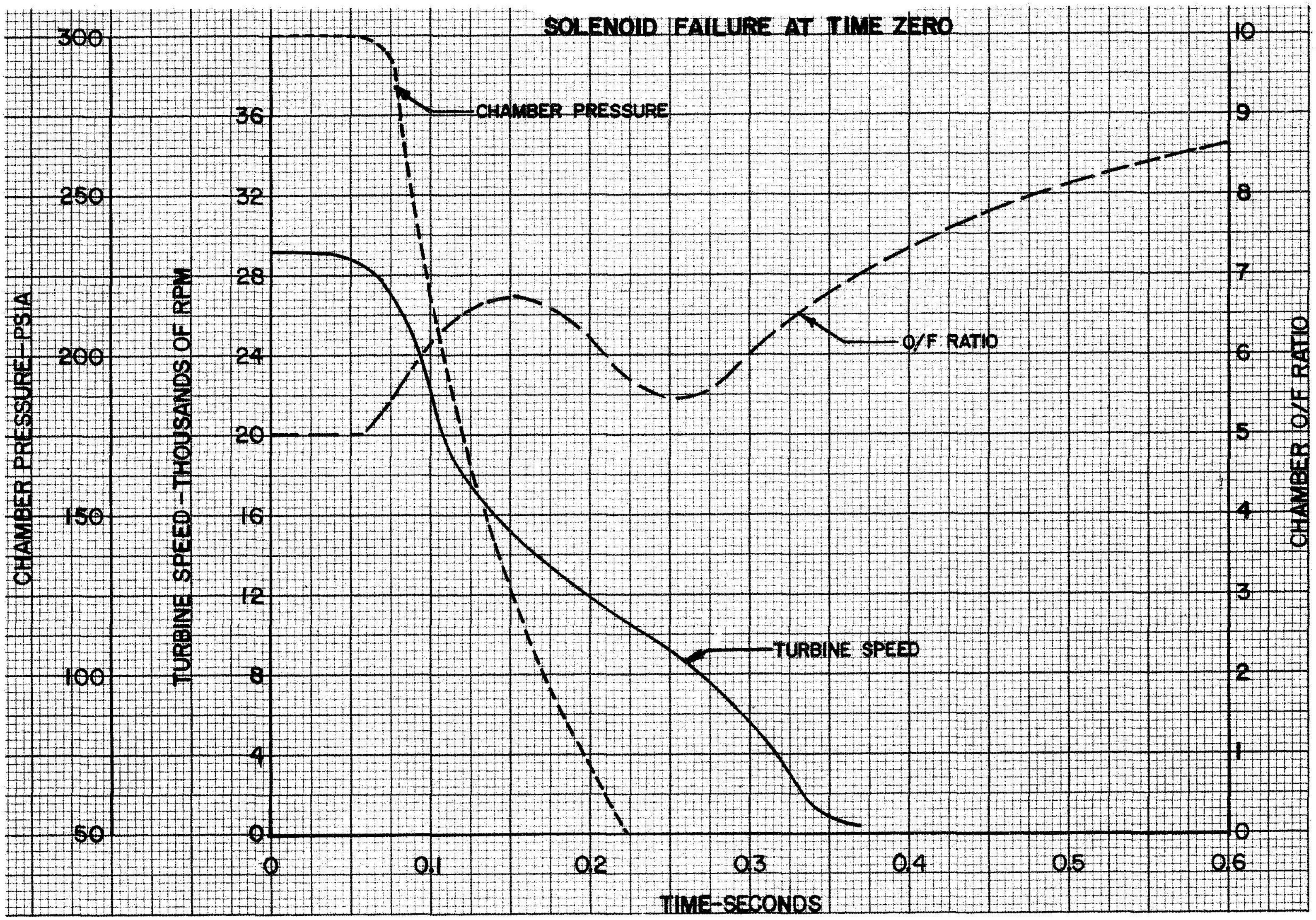


Figure X-1. Effect of Start Solenoid Failure During Steady-State Operation

DF 15405

b. Acceleration

The engine will remain shut down or shut down normally. If the helium supply is restored and the normal starting sequence is followed, the engine will be capable of normal operation.

c. Steady-State

The engine will shut down in a normal manner. If the helium supply is restored and the normal starting sequence is followed, the engine will restart, operate, and shut down normally.

d. Shutdown

Normal for this phase. No effect on subsequent operation if the helium supply is restored.

6. Failure or Shutoff of the Oxidizer Supply

a. Prestart

The oxidizer pump, valves, and injector will not cool down. Fuel will flow overboard through the cooldown valves. If the oxidizer supply is restored and the specified cooldown time allowed, the engine will start, operate, shut down, and restart normally.

b. Acceleration

Combustion will not occur. The turbopump will accelerate to approximately design speed due to residual heat in the thrust chamber, and then decelerate immediately. Fuel will flow overboard through the thrust chamber until the shutdown signal is given. If the oxidizer supply is restored, the specified cooldown time is allowed, and the chamber temperature is restored to a level within the specification limits, the engine will start, operate, shut down, and restart normally.

c. Steady-State

Propellant combustion will be terminated due to loss of oxidizer supply, and chamber pressure will decay in 0.06 second to a constant pressure of 25 to 30 psia as fuel continues to flow overboard through the thrust chamber. The turbopump will overspeed about 17% to 34,500 rpm and will then decelerate as the turbine inlet temperature drops from an operating temperature of 320°R to fuel pump inlet temperatures. If the oxidizer supply is restored and other conditions are within specification limits, the engine will restart, operate, and shut down in a normal manner. Figure X-2 shows the effect of oxidizer supply failure on steady-state operation.

d. Shutdown

Normal for this phase. No effect on subsequent operation if oxidizer supply is restored.

DF 15406

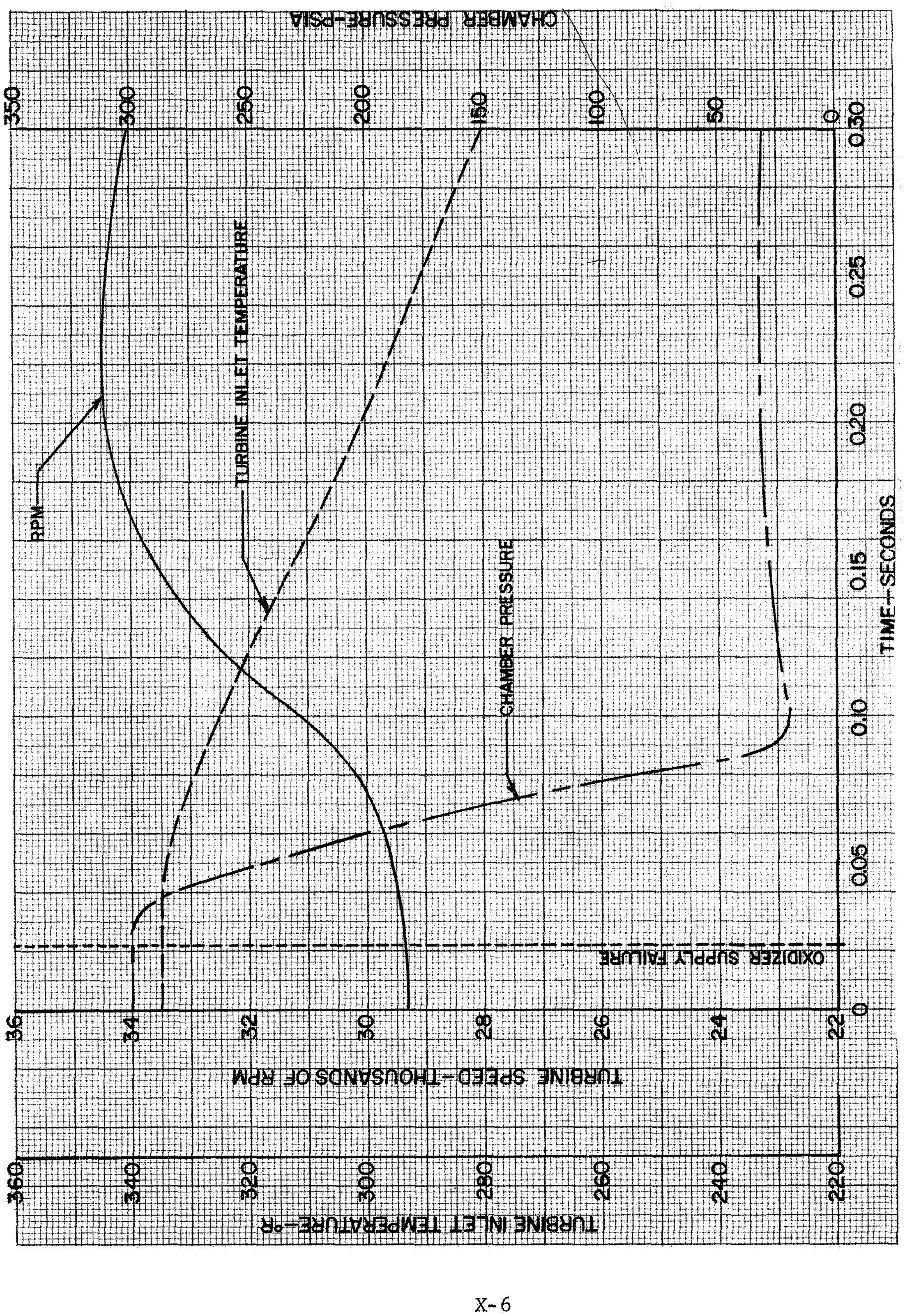


Figure X-2. Effect of Oxygen Supply Failure During Steady-State Operation

7. Failure or Shutoff of the Fuel Supply

a. Prestart

The fuel pump will not cool down. Oxidizer will flow overboard through the thrust chamber, which is normal for this phase of operation. No effect on subsequent operation if the fuel supply is restored and the specified cooldown time is allowed.

b. Acceleration

The engine will not start, and oxidizer will continue to flow overboard through the thrust chamber. No effect on subsequent operation if the fuel supply is restored and the specified cooldown time is allowed. The effects of a failure during the latter portion of the acceleration phase are similar, on a reduced scale, to failure during the steady-state phase. (Refer to paragraph 7c following.)

c. Steady-State

The turbopump will momentarily overspeed about 8.5% to 31,800 rpm, and will then decelerate rapidly. The fuel pump will cavitate and combustion will terminate. Pump inlet pressure will increase. Figures X-3 and X-4 show the effect of fuel supply failure on steady-state operation.

d. Shutdown

Normal for this phase. No effect on subsequent operation if the fuel supply is restored.

C. RESULTS — MALFUNCTIONS NOT REQUIRED BY MODEL SPECIFICATION 2272D, REVISION 1

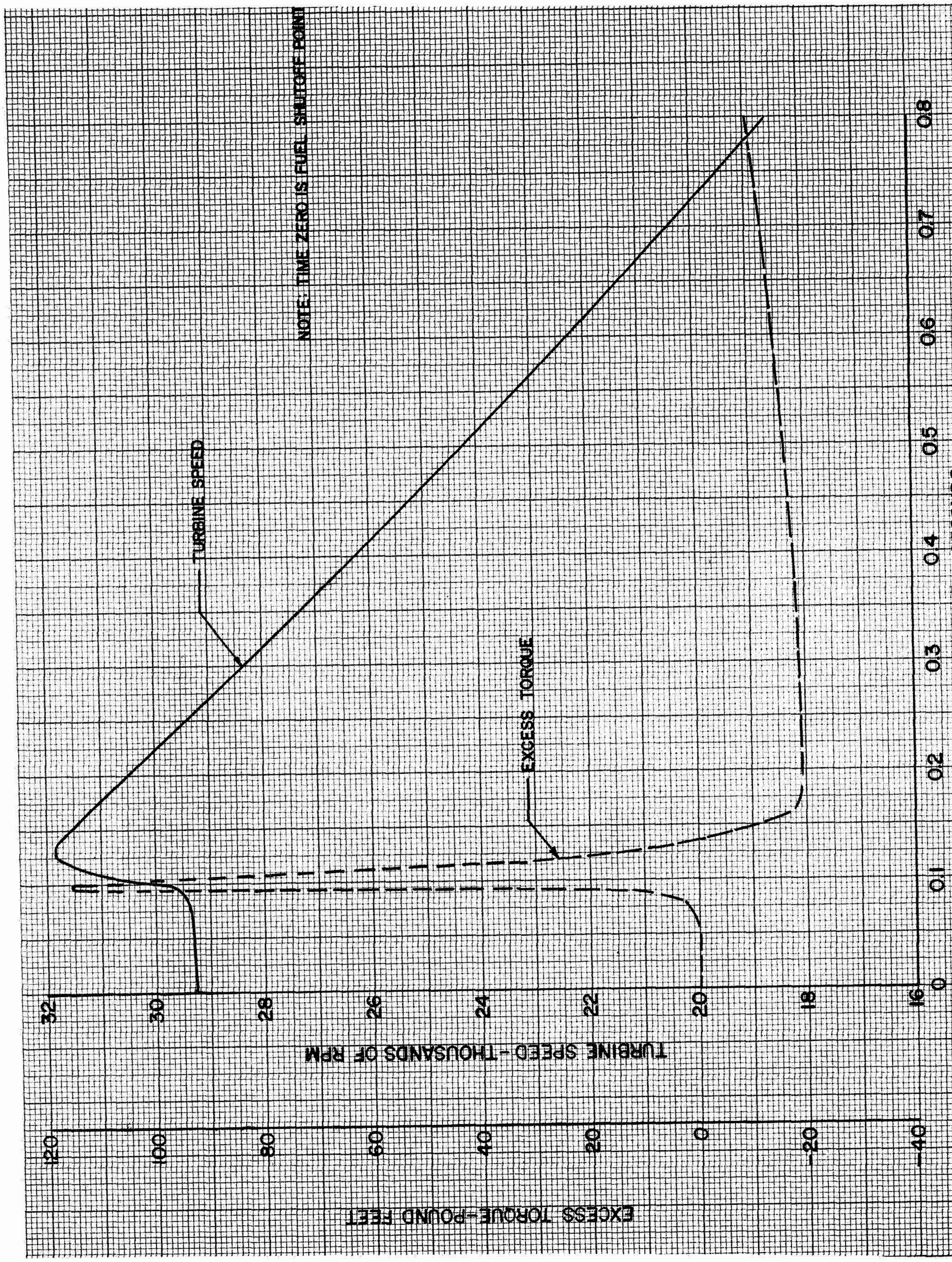
1. Failure or Shutoff of the Igniter Electrical Supply

a. Prestart

Normal for this phase of engine operation. No effect on subsequent engine operation if electrical supply is restored.

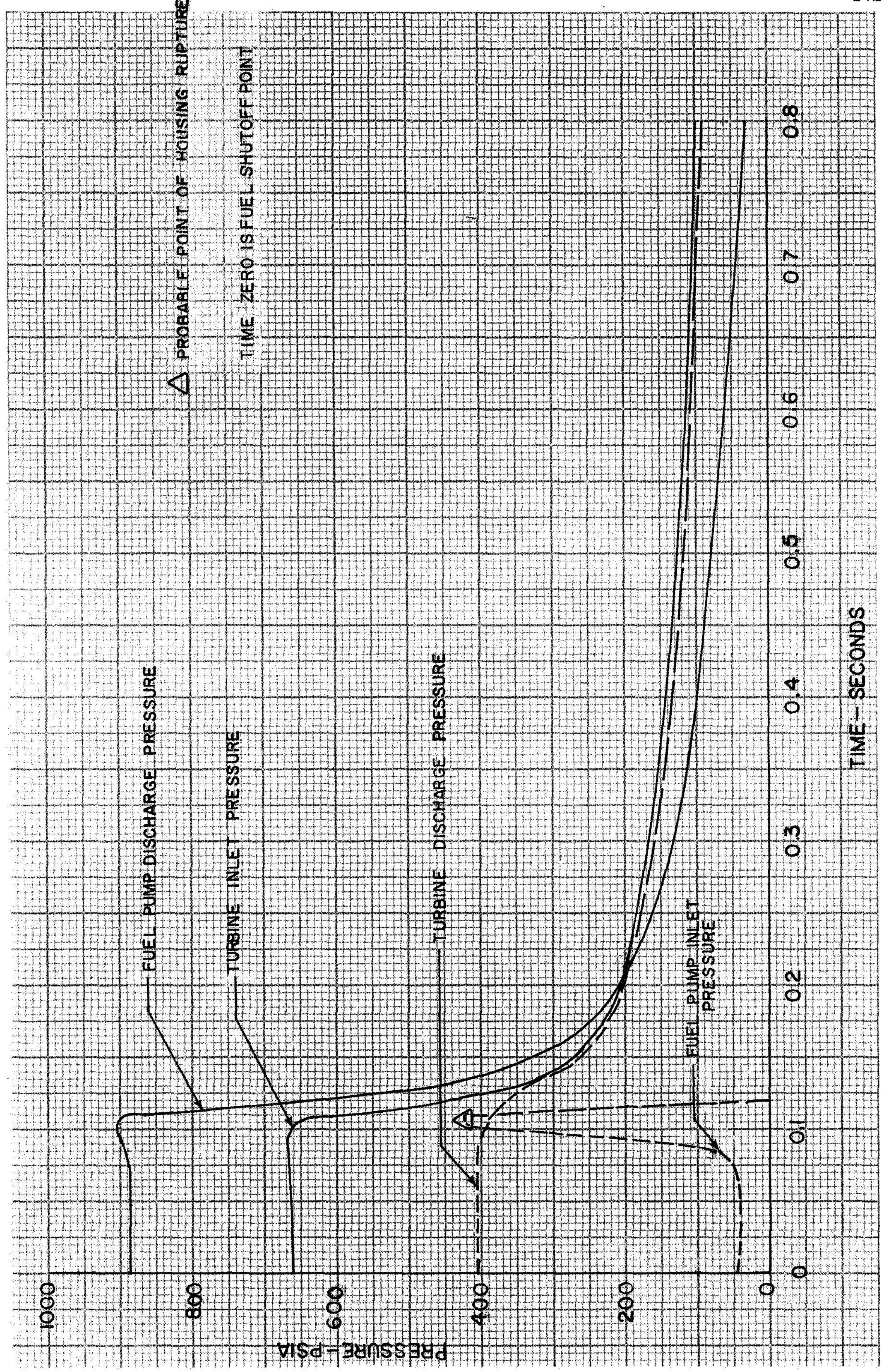
b. Acceleration

Failure of the igniter electrical supply after a combustible mixture has been ignited will not affect subsequent engine operation if the electrical supply is restored prior to the next acceleration phase. Failure of the igniter prior to the ignition of a combustible mixture will cause the turbopump to accelerate to approximately design speed due to residual heat in the thrust chamber and then decelerate immediately. Propellants will flow overboard through the thrust chamber. The chamber pressure will be low and its temperature will rapidly approach propellant temperatures because of the fuel flow through the chamber tubes and the total propellant flow through the combustion chamber. If the electrical supply is returned while the thrust chamber is filled with propellant, the engine will experience a hard start. There will be no effect on subsequent engine operation.



DF 15407

Figure X-3. Effect of Fuel Supply Failure on Turbine Speeds During Steady-State Operation



DF 15408

Figure X-4. Effect of Fuel Supply Failure on Pressure During Steady-State Operation

c. Steady-State

Normal for this phase of engine operation. No effect on subsequent engine operation if the electrical supply is restored.

d. Shutdown

Normal for this phase of engine operation. No effect on subsequent engine operation if the electrical supply is restored.

2. Electrical Supply Variations in Excess of Specifications

High voltage levels may burn out the igniter or the solenoids. The result would be as described above for failure of each component. Low voltage levels are discussed below for each phase of engine operation.

a. Prestart

No effect if the prestart solenoid valve opens.

b. Acceleration

The safe operating limits for voltage supply to the igniter are 20 volts to 30 volts dc. A low voltage level will decrease igniter firing rate and strength of spark, which could prevent ignition.

If the start signal follows the prestart signal too closely, (less than the minimum specified cooldown time), insufficient pump cooldown will prevent the engine from accelerating normally and will cause cavitation with the engine operating erratically at low thrust levels and high mixture ratios. Under these conditions there is a strong possibility that tube wall burnout will occur. If tube wall burnout does not occur, the pumps will eventually cool down and the engine will accelerate to rated thrust. Starting impulse variation between engines could become excessive and present severe guidance problems. If tube wall burnout does not occur, the engine will retain restart capability.

c. Steady-State

No effect if the solenoid valves remain open.

d. Shutdown

Normal for this phase. No effect on subsequent engine operation if the electrical supply is within specification limits.

3. Helium Supply Variations in Excess of Specifications

Helium supply pressure above the Model Specification limits will shorten the life of the control system bellows. Helium supply pressures well below Model Specification limits will also have the same effect as failure of the helium supply. (See paragraph B5 in this section.) Specific effects for moderate pressure variations below specification limits are given below.

a. Prestart

Helium supply pressure below 250 psia will prevent the inlet valves from operating, and will result in the inability to cool down the pumps and start the engine. If the supply is restored and the specified cooldown time is allowed, the engine will start, operate, and shut down normally.

b. Acceleration

A helium supply pressure between 325 and 350 psia could result in fluttering of the fuel pump bleed valves as the engine accelerates to the design point. This fluttering results in unstable operation at high mixture ratios and reduced thrust levels. The engine decelerates and operates at low speed and thrust levels. Mixture ratio increases and tube wall burnout may occur. If the helium supply is restored to a level within the specified limits and no damage was sustained by the chamber and cooldown valves, the engine will accelerate to rated thrust conditions, operate and shut down normally, and retain restart capabilities.

c. Steady-State

At approximately 325 psi the cooldown valves will open, with a resulting increase in mixture ratio and a reduction in power, thrust, and rpm. Under these conditions there is a possibility of tube wall burnout, or injector burnout at shutdown. If the helium supply is restored to a level within the specified limits and no damage was sustained by the tubes or injector, the engine will be capable of normal operation.

d. Shutdown

No effect, since the helium supply is shut off during this phase.

4. Propellant Inlet Pressure and Temperature Outside Specification Limits

a. Prestart

Low propellant inlet pressures will result in insufficient cooldown flows and inability of the engine to accelerate properly. Inlet temperature variations above the specified maximum allowable will tend to reduce the efficiency of pump cooldown. If the variation becomes excessive, insufficient pump cooldown will occur, which will result in pump cavitation during the acceleration transient. The effects of pump cavitation are described in paragraph B7c. If the pressures and temperatures are restored to levels within specification limits and if the specified cooldown time is allowed, the engine will start, operate, and shut down normally.

b. Acceleration

Low oxidizer supply pressure will result in faster turbopump acceleration rates and operation at low mixture ratios. The engine will not be damaged. Abnormally high oxidizer pump inlet pressures could result in the inability of the engine to accelerate to full rated thrust. Low fuel pump inlet pressure could prevent engine starting by reducing the energy level of the gaseous fuel entering the turbine thereby eliminating the "bootstrap" acceleration capabilities of the engine. In the case of low fuel pressure or high oxidizer pressure, the engine will operate at a high mixture ratio, which could result in tube wall burnout.

Excessively high propellant inlet temperatures will affect fluid densities and cause the pumps to deliver less than their rated flow rates. As a result, the engine will operate at a lower thrust level and, if fuel flow is low, tube wall burnout may occur. If burnout does not occur and the inlet temperatures are restored to levels within the specification limits, the engine will restart, operate, and shut down normally.

c. Steady-State

If oxidizer pressure is too low, the results are the same as described in paragraph b above. Fuel pump inlet pressure below allowable NPSP will cause fuel pump cavitation. Tube wall burnout may occur due to loss of regenerative cooling flow. This condition may restrict further operation of the engine. The effect of high inlet temperatures is the same as described in paragraph b above.

d. Shutdown

No effect since the propellants are not supplied to the engine during this phase.

5. Ambient Pressure and Temperature Outside Specification Limits

a. Prestart

Ambient pressures outside of the specified maximum allowable will cause inadequate cooldown on engines that are equipped with collector manifolds. Ambient temperatures above the specified limits will have no appreciable effect unless metal temperatures exceed 580°R, which could cause inadequate cooldown. Inadequate cooldown will affect engine operation during the acceleration phase as described in paragraph C2b. If the ambient pressures and temperatures are returned to normal and if adequate cooldown is provided, the engine will start, operate, and shut down normally.

b. Acceleration

The "bootstrap" capability of the engine is dependent on both fuel pump inlet pressure and ambient pressure. The engine may not start successfully if ambient pressure lies above the curve shown in figure X-5. However, if ignition occurs, the engine may experience a hard start with the possibility of a tube wall burnout.

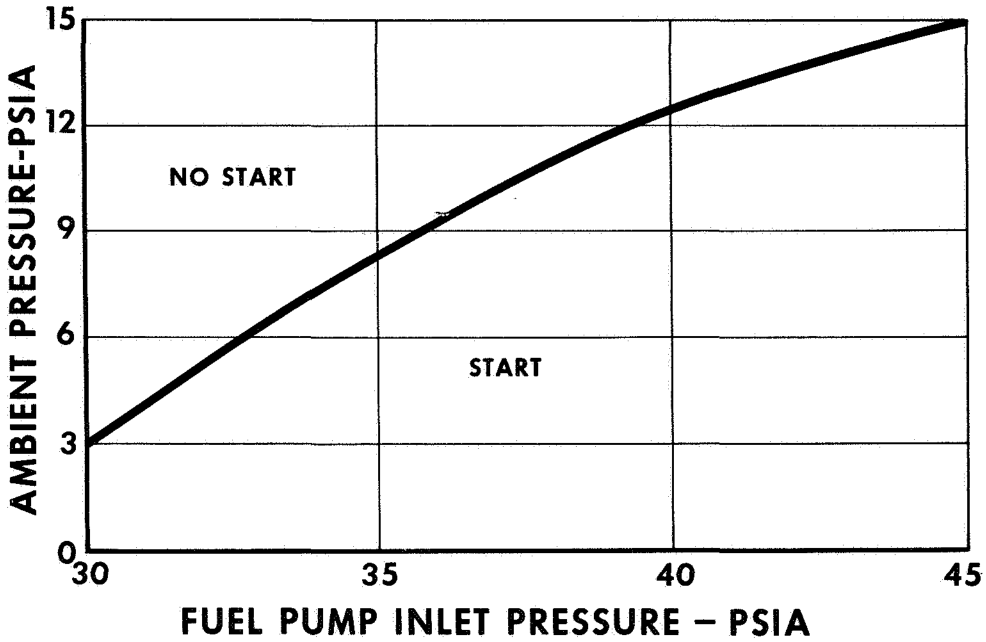


Figure X-5. RL10A-3-1 Engine Starting Limits FD 1250

If chamber temperature drops below specification limits, the engine will not reach rated speed, but will operate at reduced speed and high mixture ratio. Tube wall burnout will occur, which will render the engine inoperative.

Chamber temperatures in excess of specification limits will cause high overshoot in turbine speed and system pressures. Excessive pressure surges could result in structural failure, and high turbine speeds will cause pump cavitation. Pump cavitation will result in extremely erratic engine operation at low thrust levels and high mixture ratios, as described in paragraph C2b.

If tube wall burnout or pump cavitation do not occur, and if the ambient pressures and temperatures are returned to normal, the engine will start, operate, and shut down normally.

c. Steady-State

Ambient temperatures outside specification limits will not affect this phase of engine operation.

Ambient pressures above approximately 5 psia will suppress nozzle expansion thereby causing flow separation from the nozzle walls. Oblique shock waves off the nozzle walls destroy the boundary layer and produce hot spots at the separation points. If prolonged, this condition could cause tube wall burnout. If burnout does not occur and if ambient pressure is returned to normal, the engine will operate and shut down normally with restart capability.

d. Shutdown

No effect will be felt.

6. Failure of the Thrust Control

a. Prestart

No effect since thrust control operation is not required during this phase of engine operation.

b. Acceleration

If the thrust control fails in the full open position, the engine will not accelerate to the rated thrust level. If the thrust control fails in the full closed position, the engine will overshoot excessively at the peak of the acceleration transient. If no structural damage occurs due to the high overshoot, the engine will retain restart capability.

c. Steady-State

If the thrust control fails and remains in the closed position, the engine will operate above the rated thrust level at a low mixture ratio. If the thrust control fails and remains in the full open position, the engine will operate at a low thrust level and a high mixture ratio. Tube wall burnout may occur which would render the engine inoperative. If the thrust control sticks in a partially open position, the engine may operate near rated thrust, depending on the amount of bypass area exposed, the chamber temperature, and the fuel pump inlet pressure. If tube wall burnout does not occur, the engine can be shut down, restarted, and operated normally.

d. Shutdown

No effect since thrust control operation is not required during this phase.

7. Closing of the Main Fuel Shutoff Valve

a. Prestart

No effect. Normal for this phase of engine operation.

b. Acceleration

Fuel will be prevented from entering the combustion chamber and the engine will not start. Propellants will be lost overboard until the prestart signal is removed. The effects of a failure during the latter portion of the acceleration phase is similar to failure during the steady-state phase.

c. Steady-State

Flameout will occur and the turbine will rapidly decelerate due to the shutoff of the fuel system. Fuel pump inlet pressure will rise, as shown in figure X-6. If the pump inlet pressure reaches 450 psi during this transient, the pump inlet housing will rupture. The interstage cooldown valve will open when fuel pump discharge pressure drops below 170 psia and propellants will continue to flow overboard until the pre-start signal is removed.

d. Shutdown

If the main fuel shutoff valve prematurely closes during the shutdown transient, the effect will be the same as paragraph c above, except during the latter portion of the transient when the cooldown valves are open. Failure after the cooldown valves are open permits a normal shut-down.

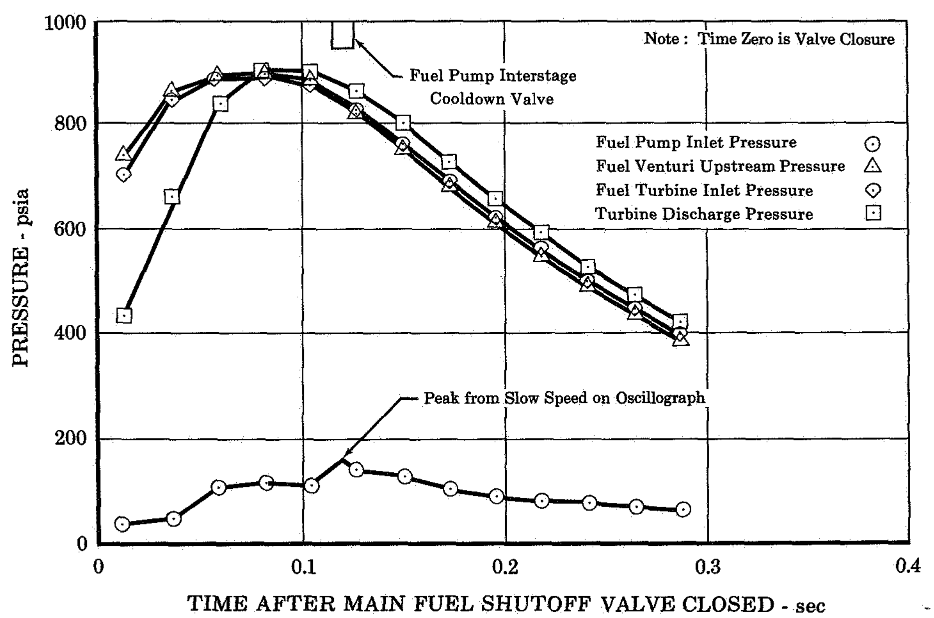


Figure X-6. Effect of Main Fuel Shutoff Valve Malfunction During Steady-State Operation

APPENDIX A
STRESS DATA

Stresses of major structural components of the engine are listed in this appendix. The data include the following:

1. Load characteristics of RL10A-3-1 gears, shown in table A-1
2. Propellant injector stresses, shown in table A-2
3. Thrust chamber stresses, shown in figure A-1
4. Fuel pump impeller stresses, shown in figure A-2
5. Turbine rotor stresses, shown in figure A-3.

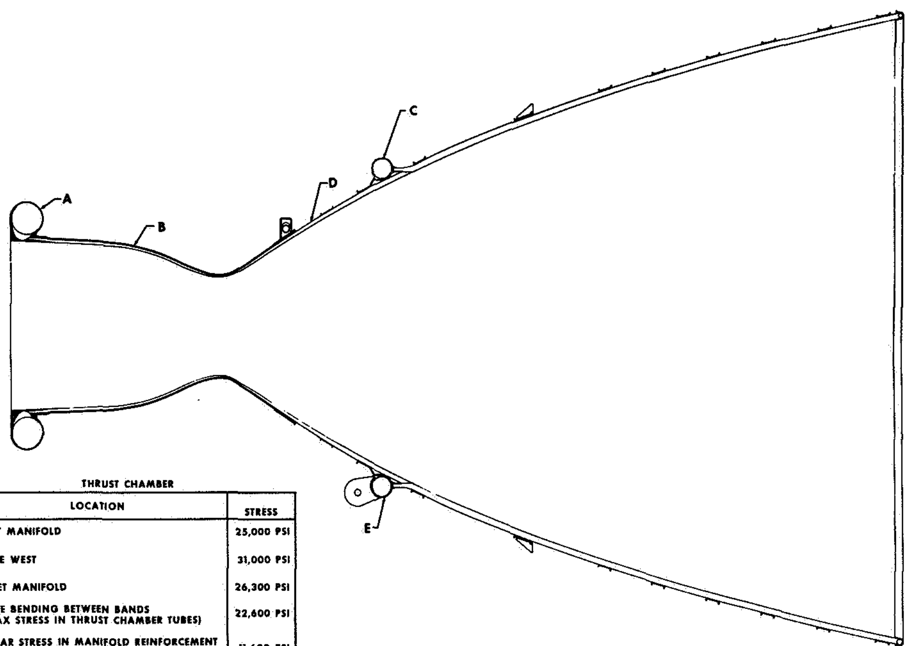
Table A-1. Load Characteristics of RL10A-3-1 Gears

Characteristics	RL10A-3-1 Shaft Gear and Idler Gear Mesh	
	Fuel Pump	Oxidizer Pump
Pitch line velocity, ft/min	15,766	15,766
Sliding velocity (max), ft/min	4,060	2,272
Tangential load (continuous), lb	242	242
Tangential load (momentary), lb	378	378
Hertz stress (continuous), psi	69,600	66,000
Hertz stress (momentary), psi	87,000	82,500
Dynamic Load (continuous), lb	1,491	1,403
Beam fatigue strength, lb	1,865	1,857
Dynamic load (momentary), lb	1,756	1,666
Static beam strength, lb	3,849	3,832

Table A-2. Propellant Injector Stresses *

	Calculated Stresses, psi	Allowable Stresses, psi
Cone No. 1		
Bending stress	30,500	30,500
Weld shear stress	10,000	13,000
Cone No. 2		
Bending stress	70,000	82,500
Tensile stress in post connecting cone No. 1	28,000	55,000
Tensile stress in post connecting cone No. 3	18,400	55,000
Cone No. 3		
Bending stress	70,000	82,500
Weld shear stress	13,000	30,000

* See figure I-22 for cone locations



THRUST CHAMBER

LOCATION	STRESS
A. EXIT MANIFOLD	25,000 PSI
B. MAE WEST	31,000 PSI
C. INLET MANIFOLD	26,300 PSI
D. TUBE BENDING BETWEEN BANDS (MAX STRESS IN THRUST CHAMBER TUBES)	22,600 PSI
E. SHEAR STRESS IN MANIFOLD REINFORCEMENT IN LINE WITH ACTUATING LUG LOAD	11,600 PSI

Figure A-1. Calculated RL10A-3-1 Thrust Chamber Stresses FD 1553A

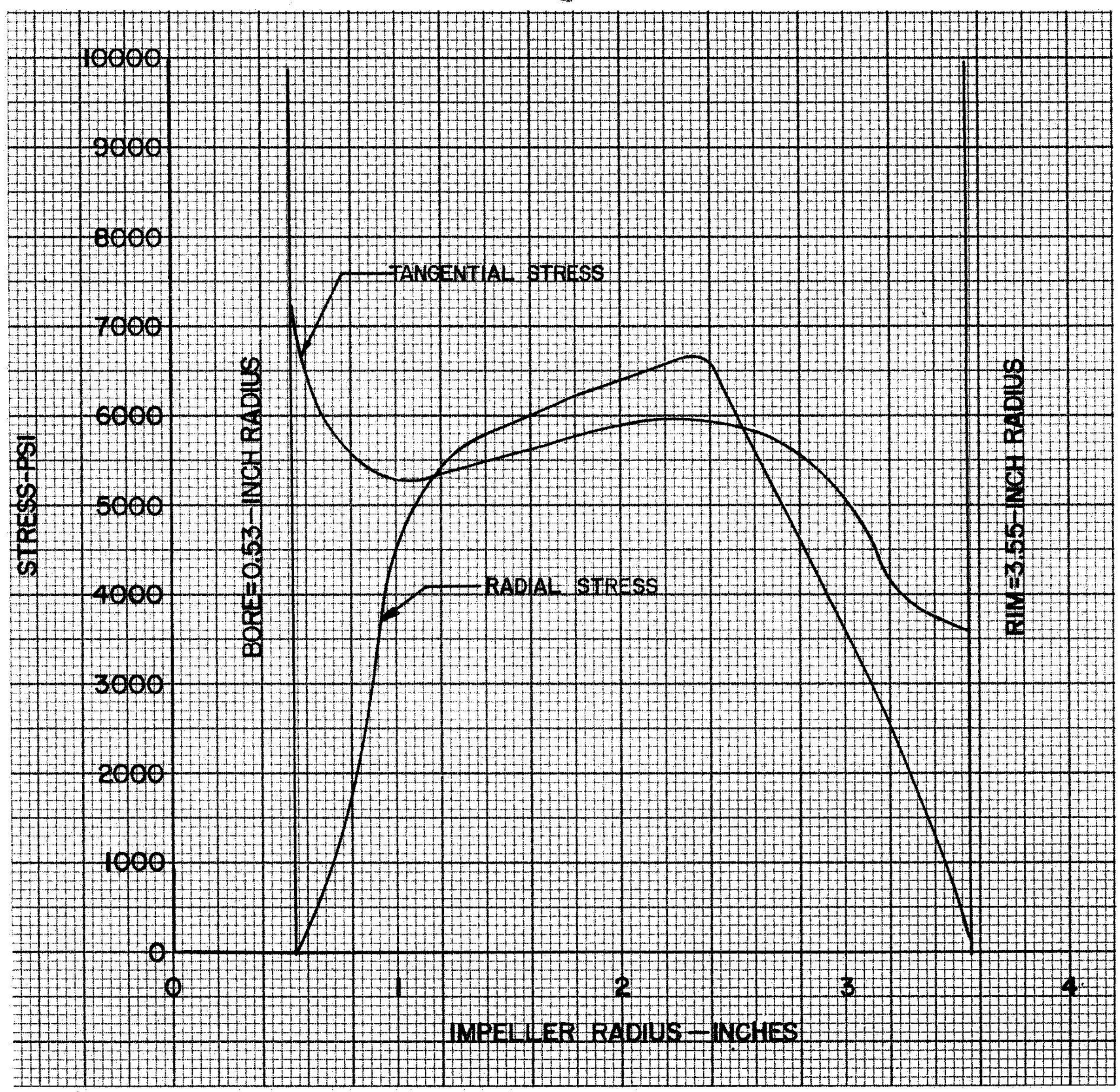


Figure A-2. Calculated Fuel Pump Impeller Stresses at 30,000 rpm DF 15412

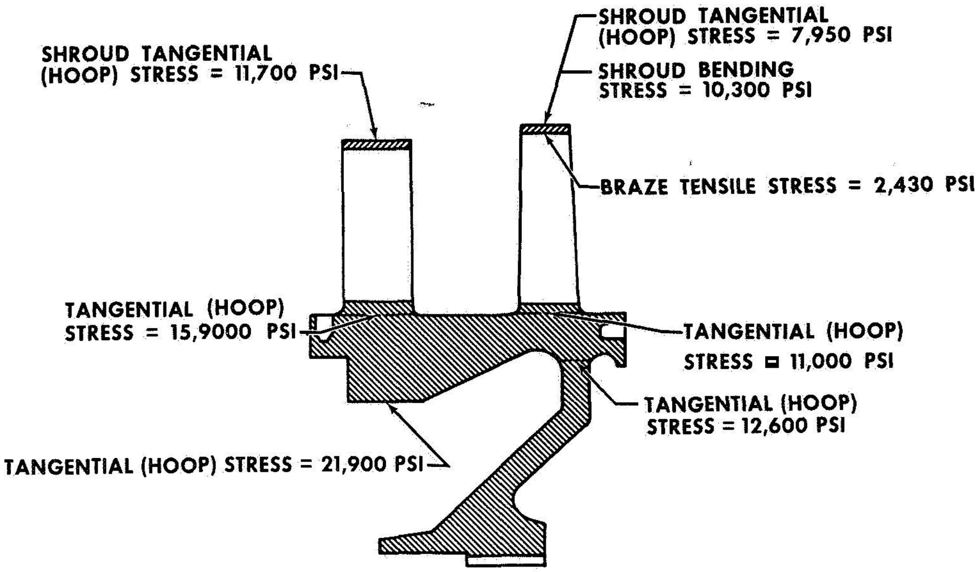


Figure A-3. Turbine Rotor Stresses FD 1555A

APPENDIX B
RL10A-3-1 TURBOPUMP DATA

A. TURBOPUMP BALANCING DATA

1. Fuel Pump

The fuel pump impellers are statically balanced within 0.001 oz-in. The turbine rotor is dynamically balanced within 0.001 oz-in. at 2000 rpm. The heavy sides of the balanced parts are marked.

The impellers and rotor are assembled on the shaft with the center impeller heavy side opposite the heavy sides of the outside impeller and the rotor. The assembly is then dynamically balanced within 0.002 oz-in. at 5000 rpm.

2. Oxidizer Pump

The inducer and impellers are statically balanced within 0.001 oz-in., and the heavy sides are marked.

The parts are assembled on the shaft with the heavy sides 180 degrees apart. The assembly is dynamically balanced to within 0.001 oz-in. at 2000 rpm.

3. Idler Gear

The idler gear is statically balanced to within 0.003 oz-in.

B. PERFORMANCE DATA

The following curves on turbopump performance are included in this appendix:

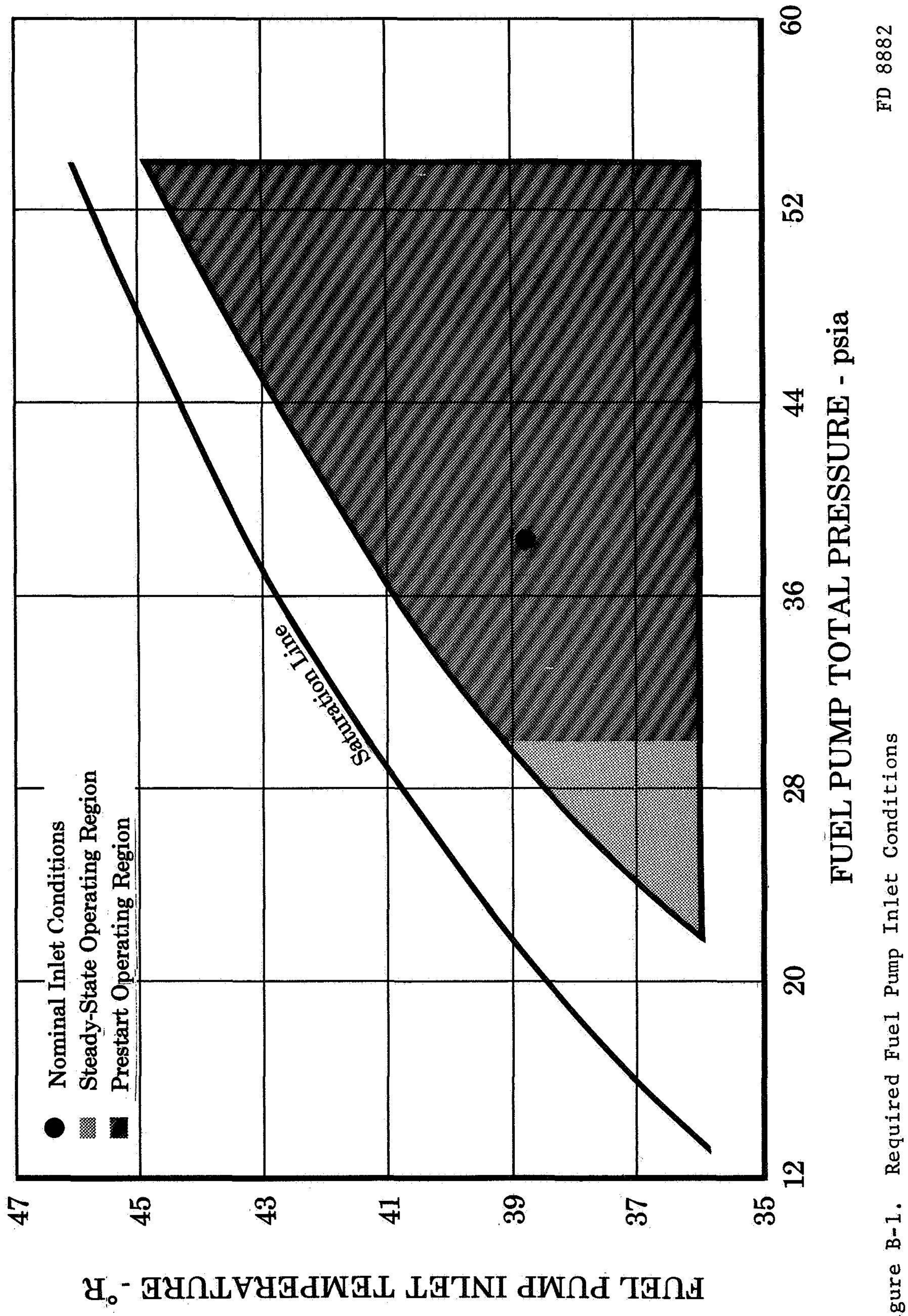


Figure B-1. Required Fuel Pump Inlet Conditions

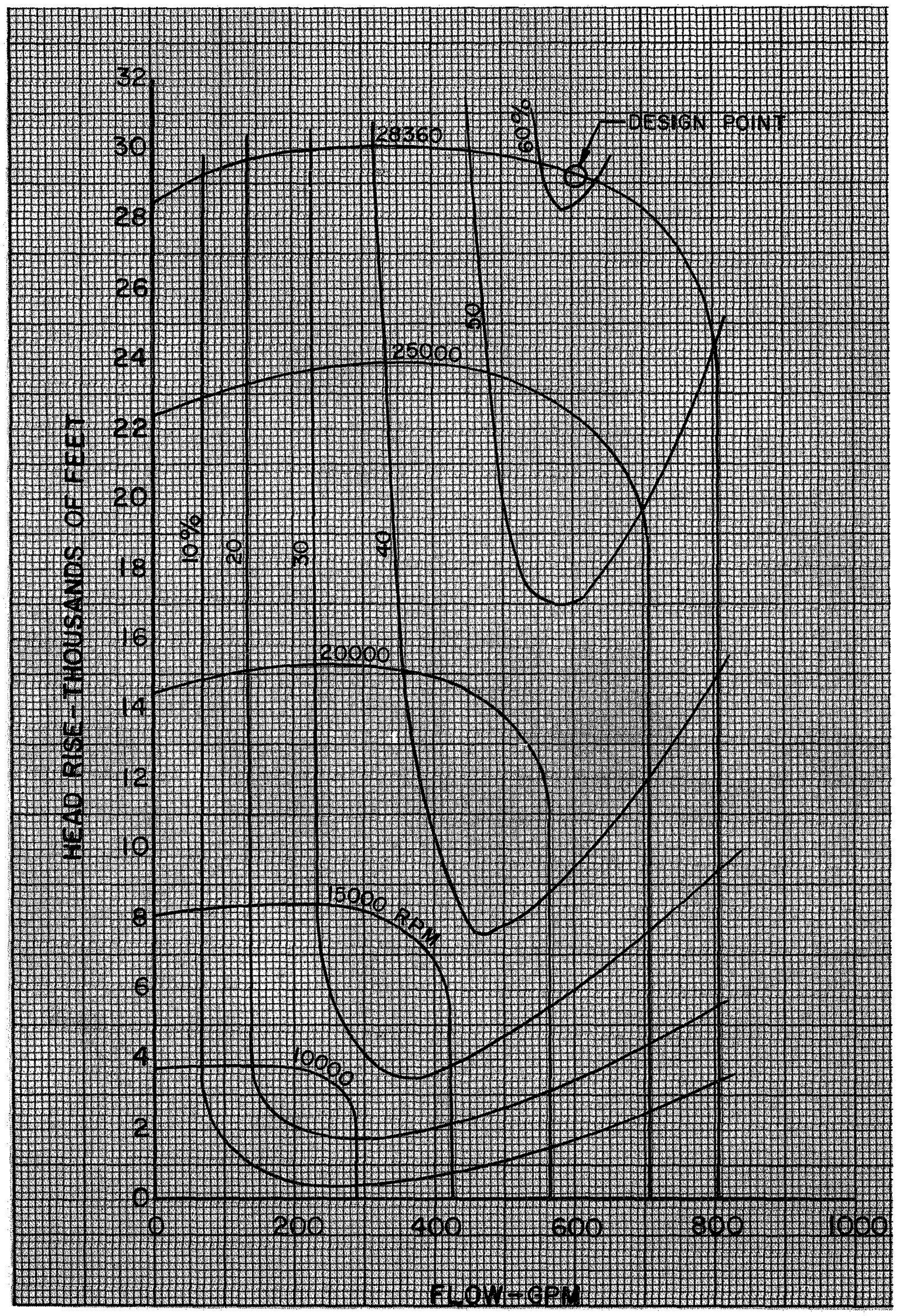


Figure B-2. RL10A-3-1 Fuel Pump Predicted Performance

DF 21540

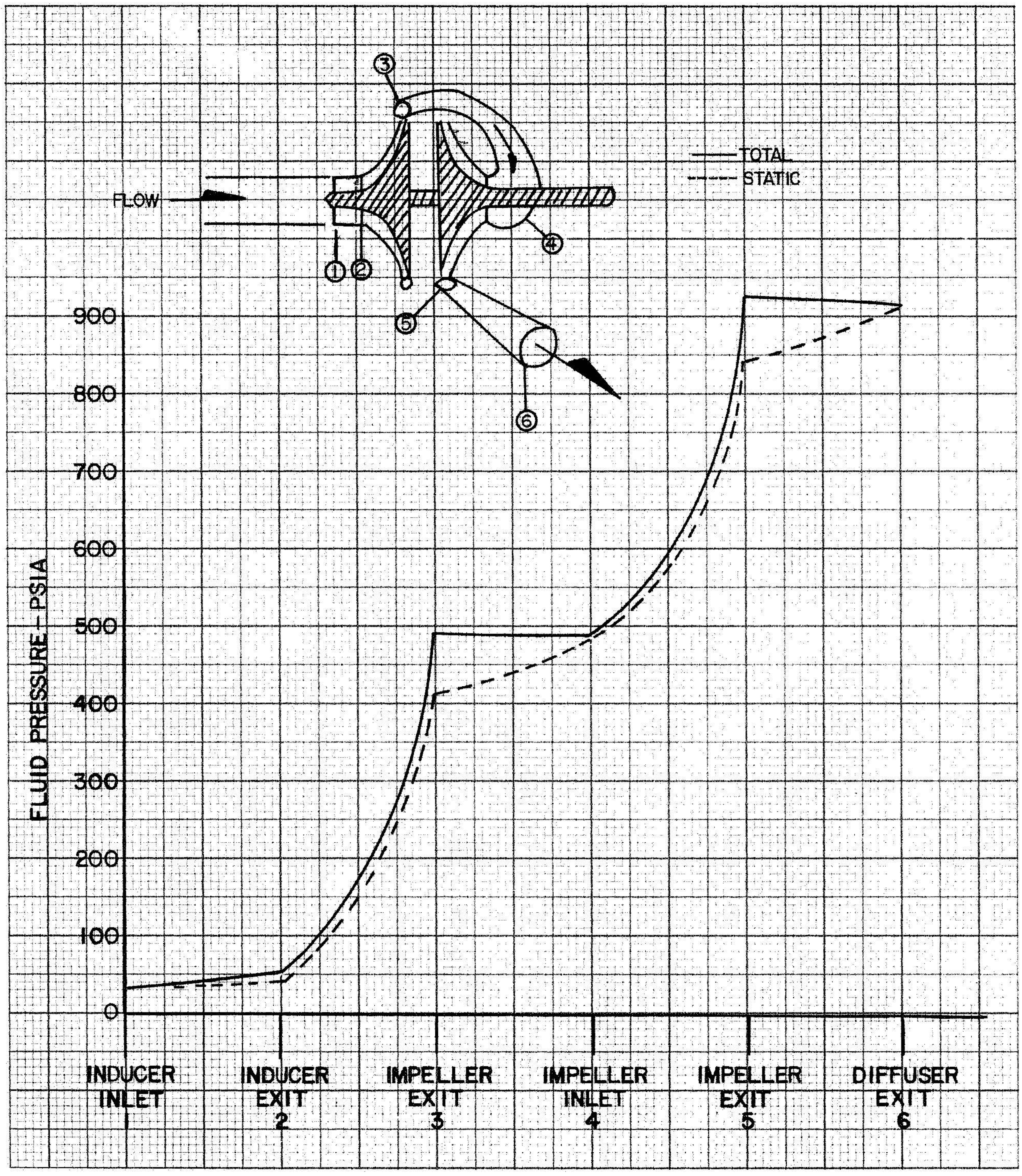
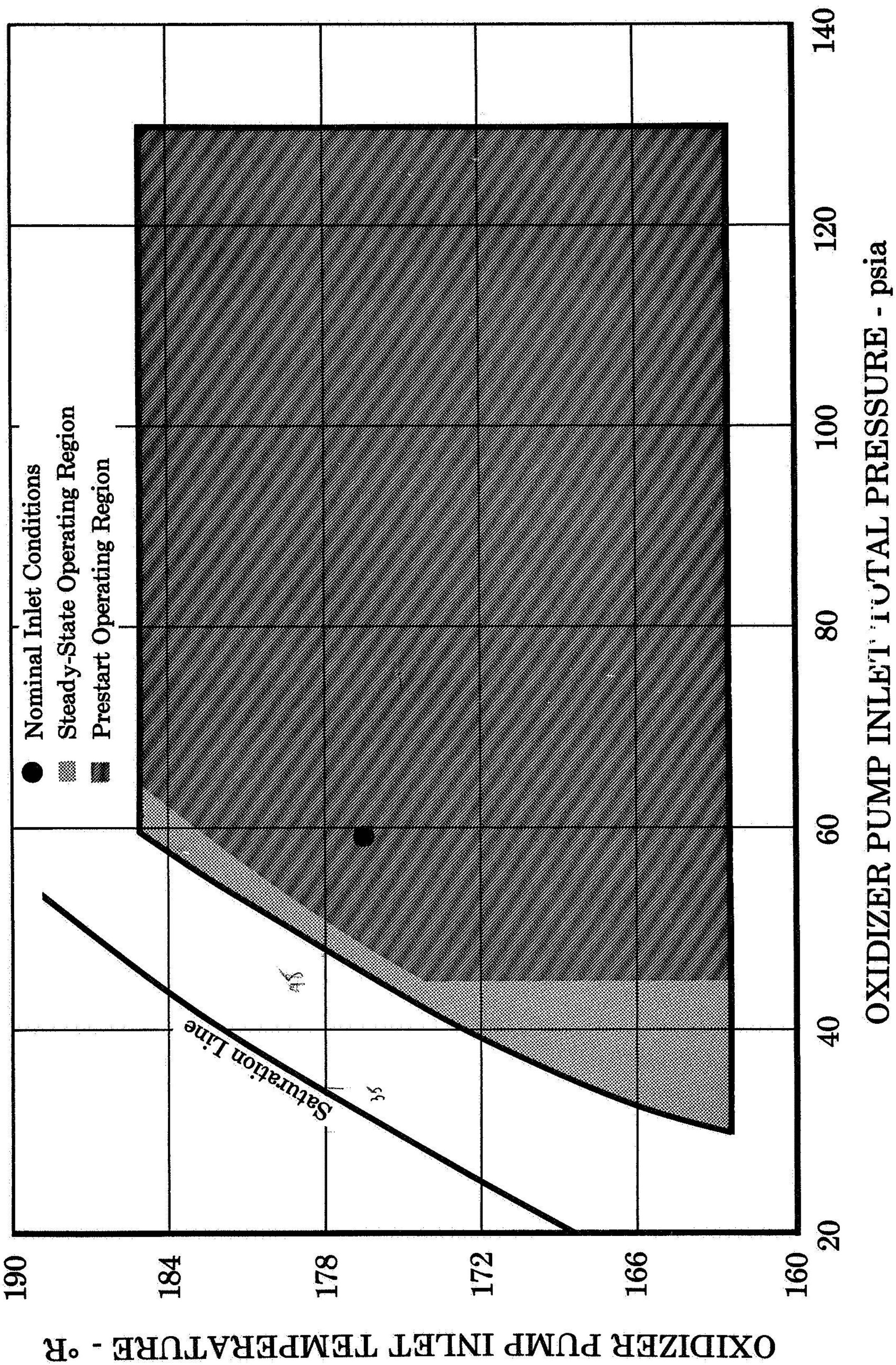


Figure B-3. Predicted RL10A-3-1 Fuel Pump Pressure at 30,000 rpm

DF 15415



FD 8883

Figure B-4. Required Oxidizer Pump Inlet Conditions

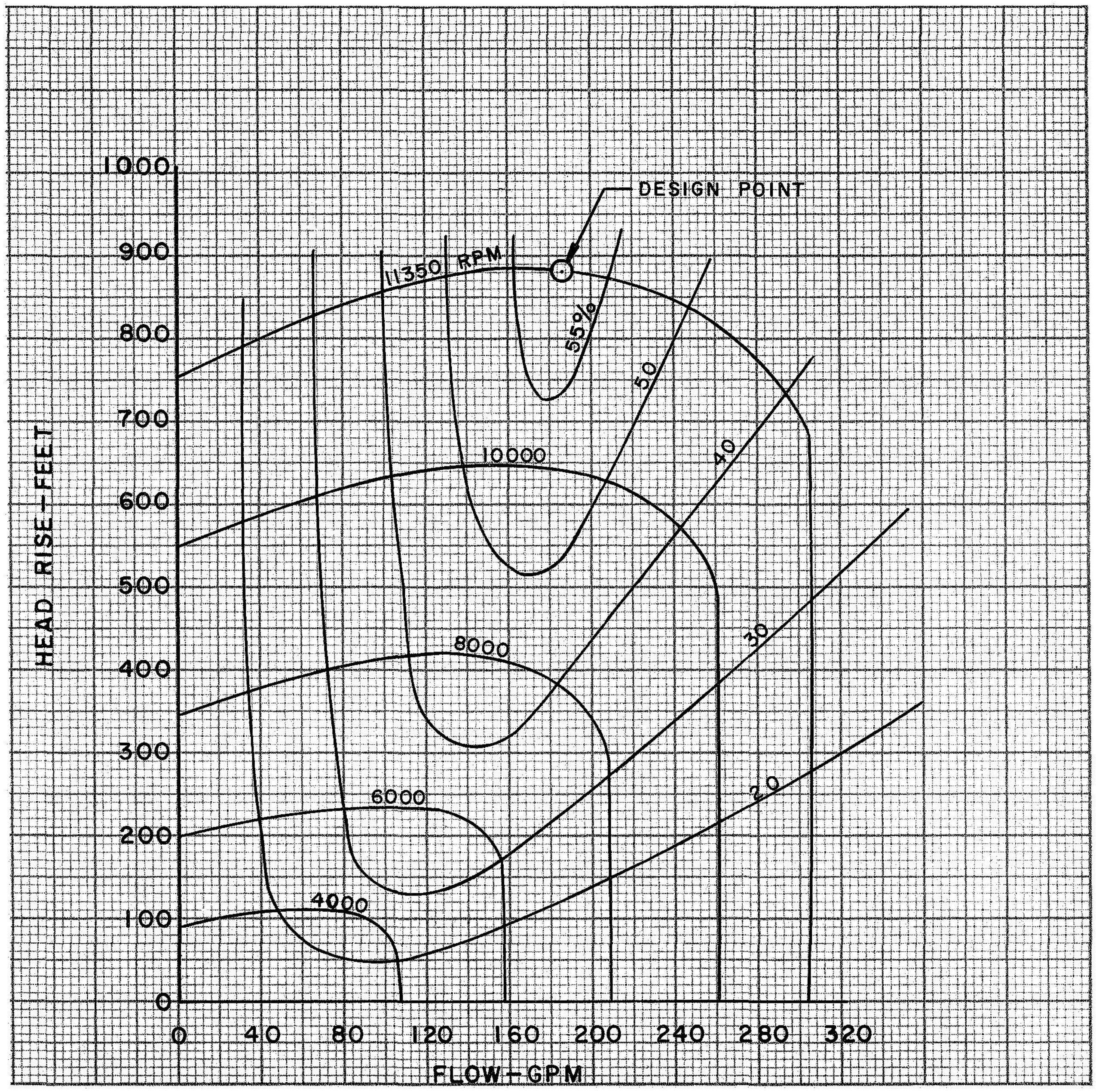


Figure B-5. RL10A-3-1 Oxidizer Pump Predicted Performance DF 21539

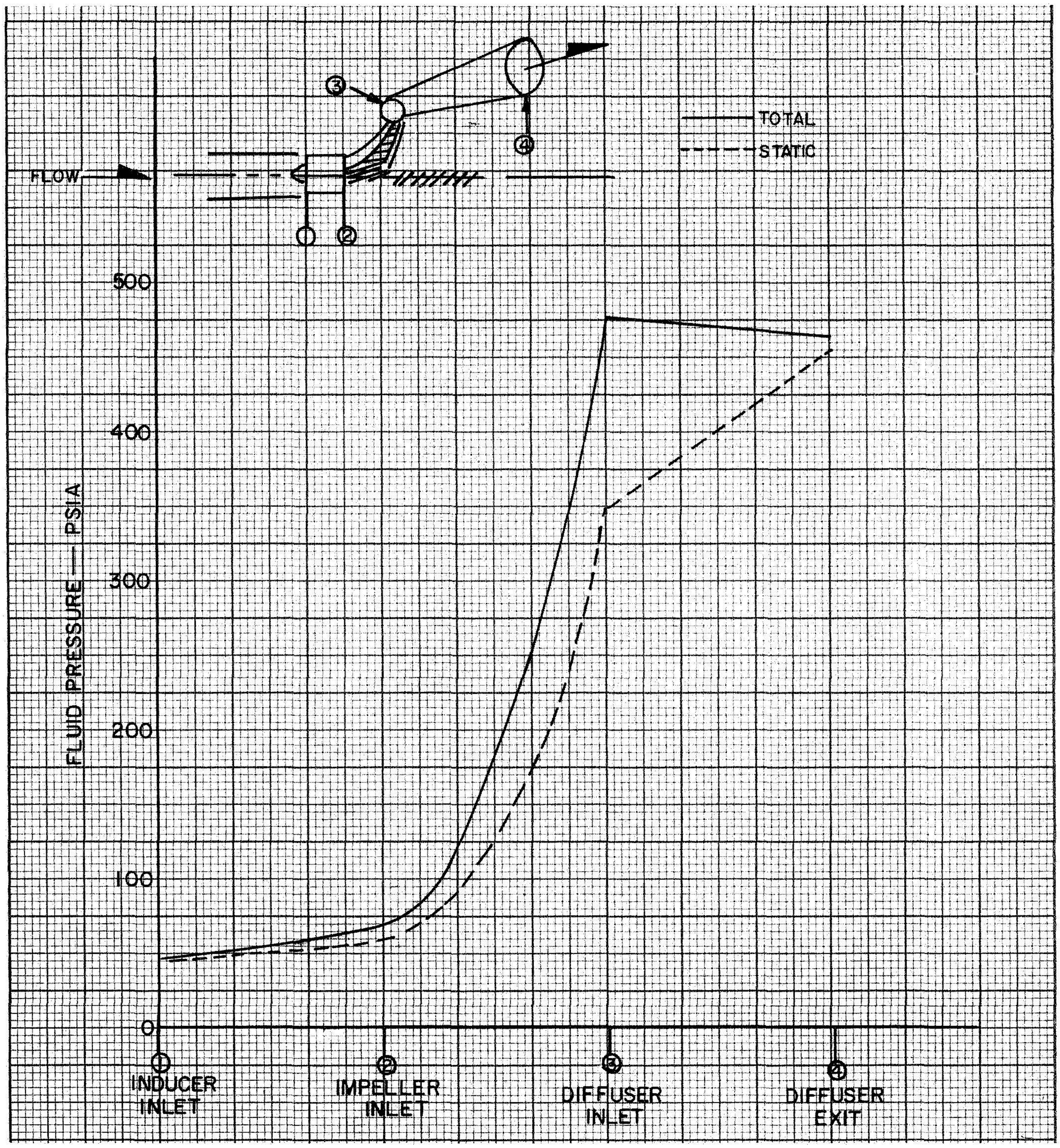


Figure B-6. Predicted RL10A-3-1 Oxidizer Pump Pressures at 12,000 rpm DF 15418

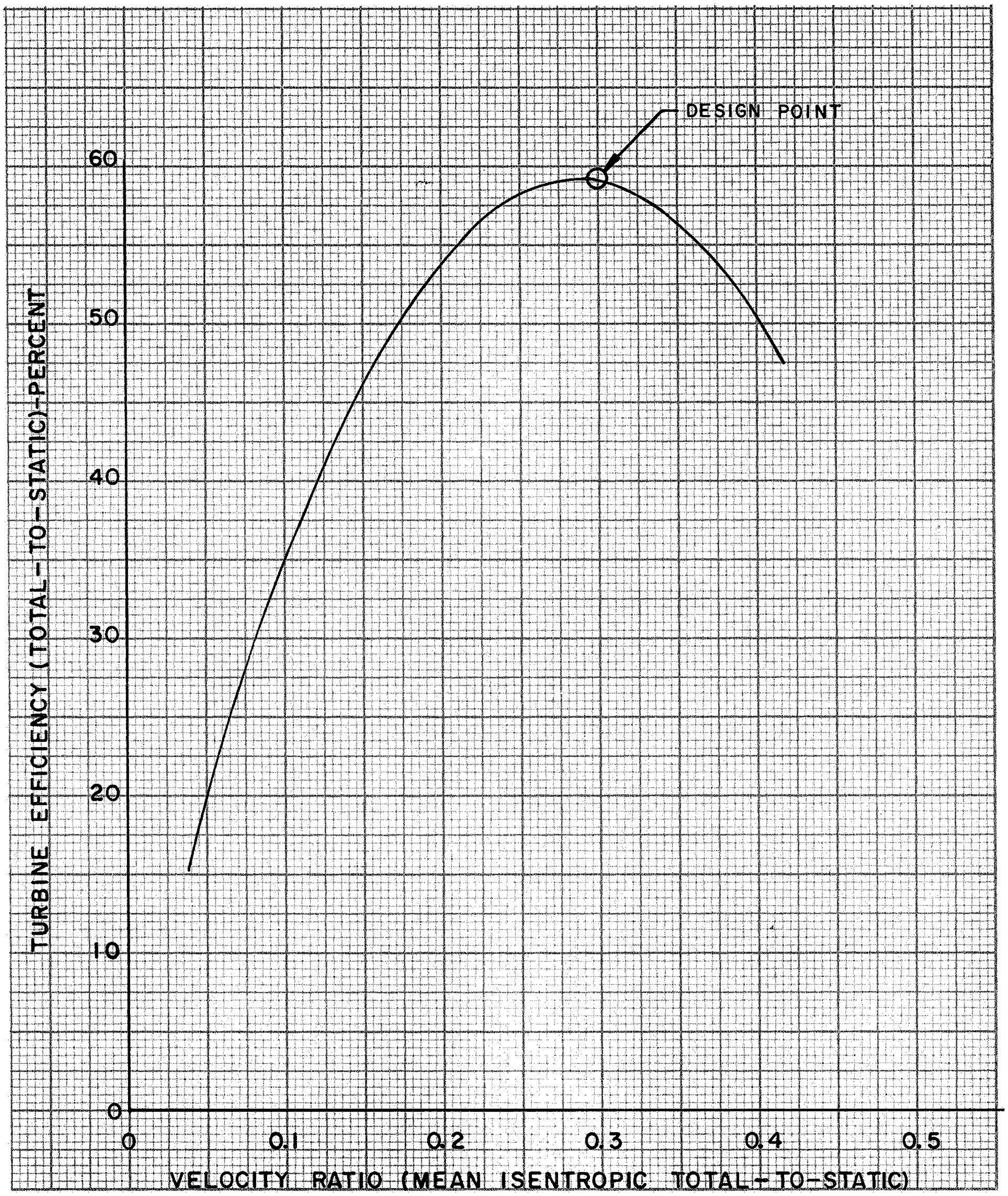


Figure B-7. Turbine Efficiency DF 21538

APPENDIX C
RL10A-3-1 CONTROL SYSTEM

The design requirements of the RL10A-3-1 thrust control include the prevention of excessive thrust overshoot during the starting transient as well as providing for stable operation at design point conditions. Analytical data, supported by engine running, have shown that the overshoot of the engine can be controlled to within allowable limits by adding the pneumatic reset feature described in Section I, paragraph A6, to the original design thrust control.

Figure C-1 shows the basic control block diagram of the engine.

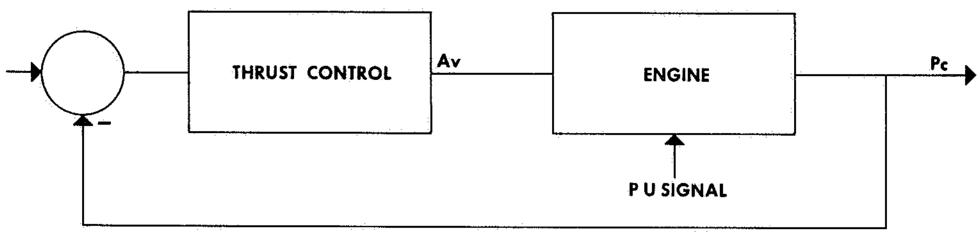


Figure C-1. Control System Simplified Block Diagram FD 3157

The block diagram shows that the controller must regulate the chamber pressure of the engine to some referenced value for various propellant utilization input signals. These utilization signals, which change engine mixture ratio, cause the engine to operate at various different power levels. Therefore, depending on the gain of the control, various amounts of droop in engine thrust will occur with changing mixture ratio.

To clarify the stability problems peculiar to this system, the linearized control block diagrams of the engine and control are shown in figures C-2 and C-3, respectively. It can be seen from these figures that the response of the engine is primarily determined by the polar moment of inertia of the turbopump rotating parts and the physical volumes of the fuel side. The diagrams also indicate that the response of the control is determined by the time constant of the servochamber and the natural frequencies of the spring-mass assemblies.

In addition to the major control loop, a secondary loop exists. This loop, which has become known as the "fast" loop, or more accurately the "negative phase lead" loop, is shown in the engine block diagram as the main forward feed line, and it includes all feedbacks to summing junctions on this line. Isolating this loop from the total system, and assuming oxidizer and venturi flow to be constant, a new block diagram, as shown in figure C-4, can be drawn. From this system transfer function $P_{co}/P_{c1} = K\tau_1 S/(1 + \tau_1 S)(1 + \tau_2 S)$ can be derived if the turbine is assumed to be choked. If only small variations in bypass area are considered, this assumption is valid. As shown by the Bode diagram in figure C-5 this gives an increasing gain and decreasing phase angle with increasing frequency.

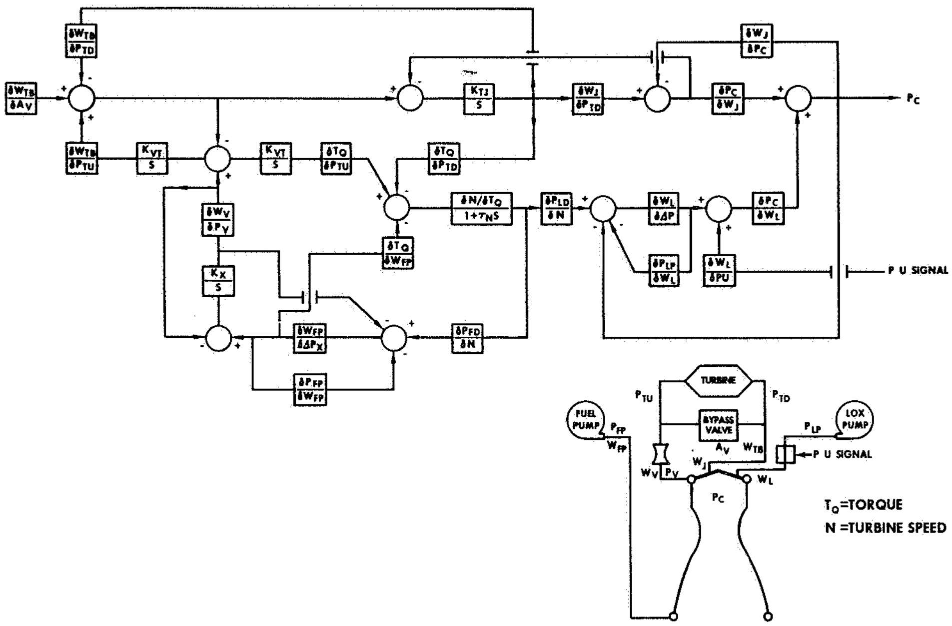


Figure C-2. Linearized Block Diagram of Engine FD 3155

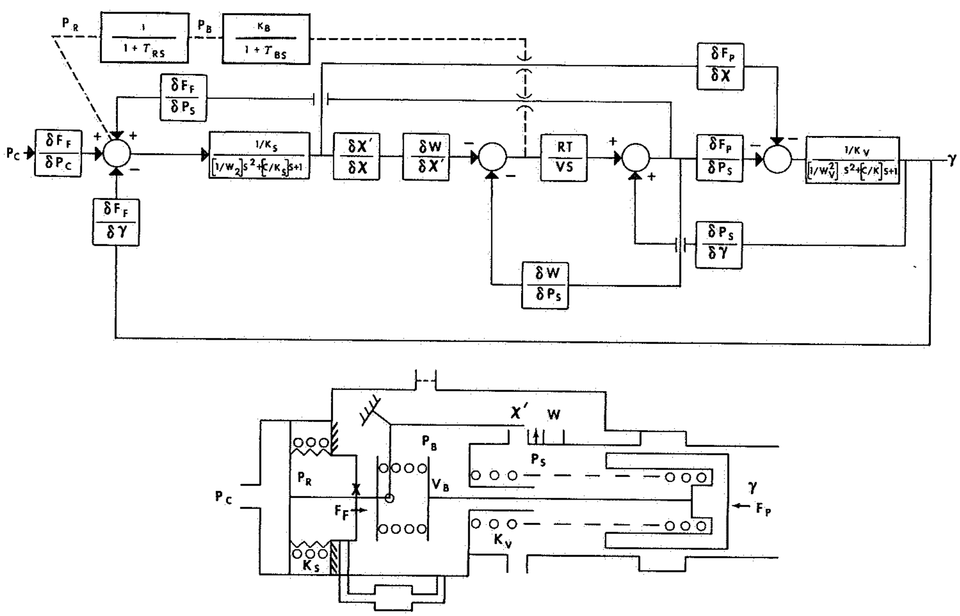


Figure C-3. Linearized Block Diagram of Thrust Control FD 3152A

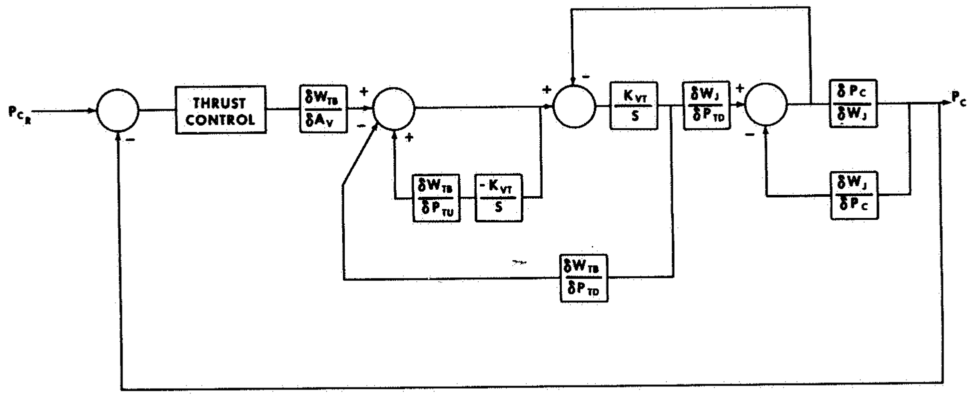


Figure C-4. Fast Loop Isolated from Engine FD 3144

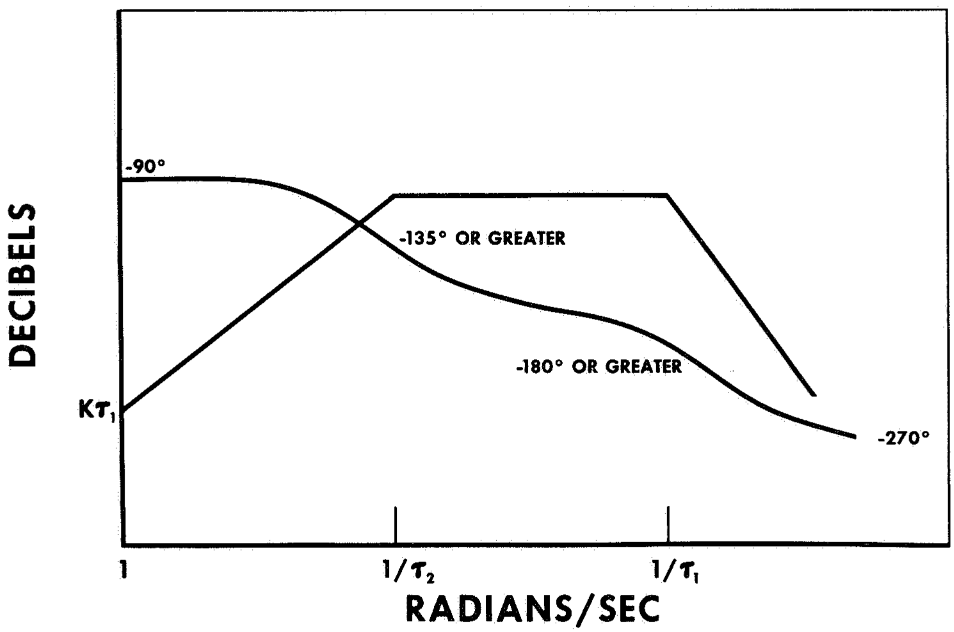


Figure C-5. Typical Bode Diagram for Fast Loop FD 3158

Because this characteristic in the system is undesirable, the effect must be minimized. To do this, several possibilities exist, the most obvious possibility is to decrease the gain "K" of the system. In figure C-6, it can be seen that "K" is primarily a function of the two partials, $\partial W_{TB}/\partial A_V$ and $\partial P_C/\partial W_J$. The value of these partial derivatives cannot be changed without affecting engine performance. In addition to "K," the loop gain could be decreased by changing τ_1. As shown by the diagram, this factor is a function of the turbine inlet volume, turbine area, pressure ratio across the turbine, and bypass and turbine inlet temperature. It is obvious that of the above, only the system volume can be changed since a change in any other parameter would affect the overall engine performance. In light of this, the system volume has been reduced to its smallest possible value.

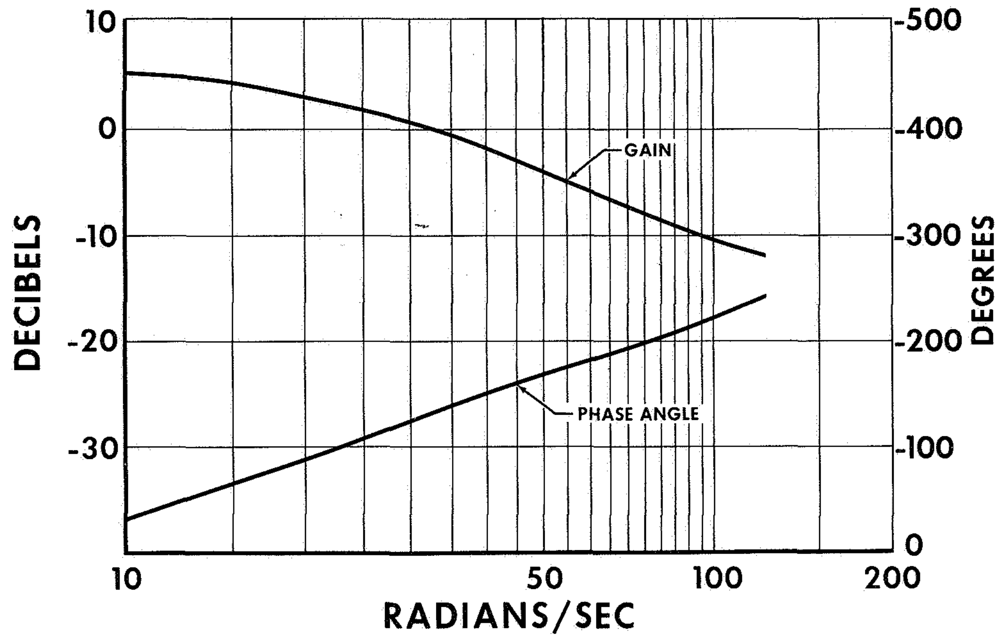


Figure C-6. Open Loop Response of Engine Plus Control (Bode Diagram) FD 3156

Another method of reducing the gain of this loop would be to increase τ_2 which would increase the frequency at which the first corner occurs, thereby reducing the maximum amplitude of the loop. This would involve increasing the volume downstream of the turbine. In addition to the time constant and gain changes mentioned above, compensating networks could be added in the feedback path. Physically, this feedback path is the chamber pressure sensing line, and the response characteristics of it could be represented by a first order lag. Increasing the time constant of this function τ_3 will decrease the gain of the system; however, it will also produce additional phase lag.

Analog studies to date have shown that the changes to τ_2 and τ_3 that are possible without adversely affecting the engine's transient performance will not significantly reduce the gain of the fast loop. Therefore, to further minimize the effect of this loop, the control should have the lowest gain possible. This then dictates the control gain.

With the effect of this fast loop minimized by the reduction of τ_1 and the controller gain, the engine is stable. This is shown by the Bode plot in figure C-6, and the Nyquist diagram in figure C-7. These curves that were derived from the results of an analog simulation of the engine indicate that a gain margin of 5 db and a phase margin of 40 degrees exist.

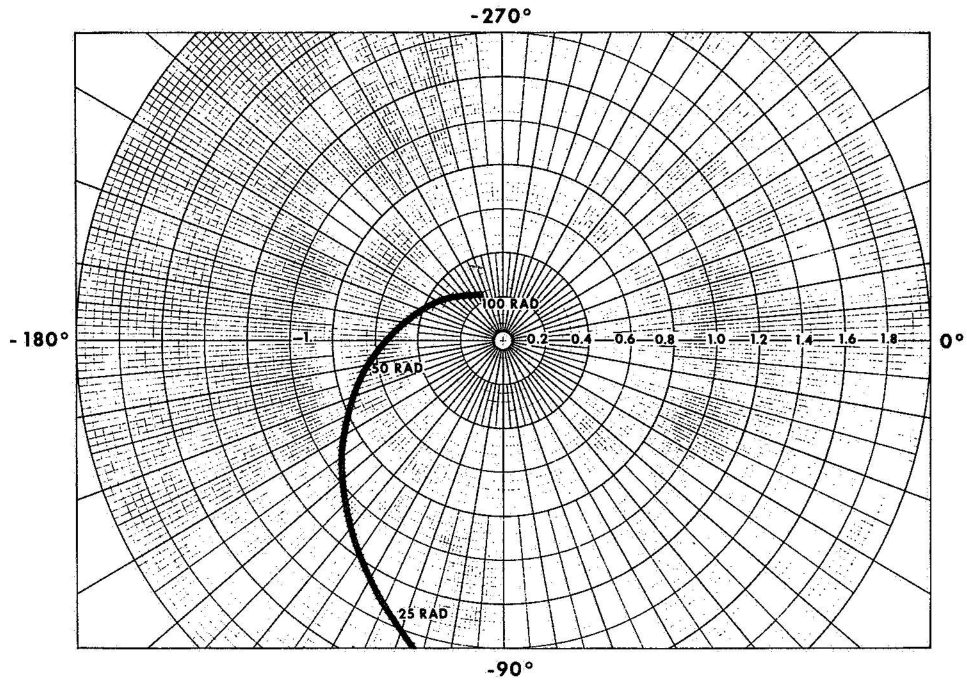


Figure C-7. Open Loop Response of Engine Plus Control (Nyquist Diagram) FD 3165

APPENDIX D
COMBUSTION AND FLOW DATA

The following curves on combustion and flow data are included in this appendix:

Table D-1. Oxidizer Inlet Valve Specifications

1. Oxidizer Side

Rated pressure, psia	26 to 130
Proof pressure, psig	200 -
Fluid temperature, °R	165 to 177
Rated flow, lb/sec	29.40
Pressure drop	Equivalent line size x 1.5
Burst pressure, psig	260 -

2. Actuation Medium (Helium Gas)

Actuation pressure, psia	450 ± 50
Actuation proof pressure, psig	600
Helium temperature, °F	-320 to +160
Burst pressure, psig	1000

3. Ambient Conditions

Temperature, °R	-320 to +160
Pressure, psia	0 to 15

4. Durability (closed-to-open-to-closed), cycles — 1500 minimum

Table D-2. Fuel Inlet Valve Specifications

1. Fuel Side

Rated pressure, psia	30 ± 2
Proof pressure, psig	150
Fluid temperature, °R	37.8 to 41
Rated flow, lb/sec	5.88
Pressure drop	Equivalent line size
Burst press -	

2. Actuation Medium (Helium Gas)

Actuation pressure, psia	450 ± 50

Table D-2.
(Continued)

Actuation proof pressure, psig	600
Helium temperature, °F	-320 to +160

3. Ambient condition

Temperature, °F	-297 to +160
Pressure, psia	0 to 15

4. Durability (closed-to-open-to-closed), cycles — 1500 minimum

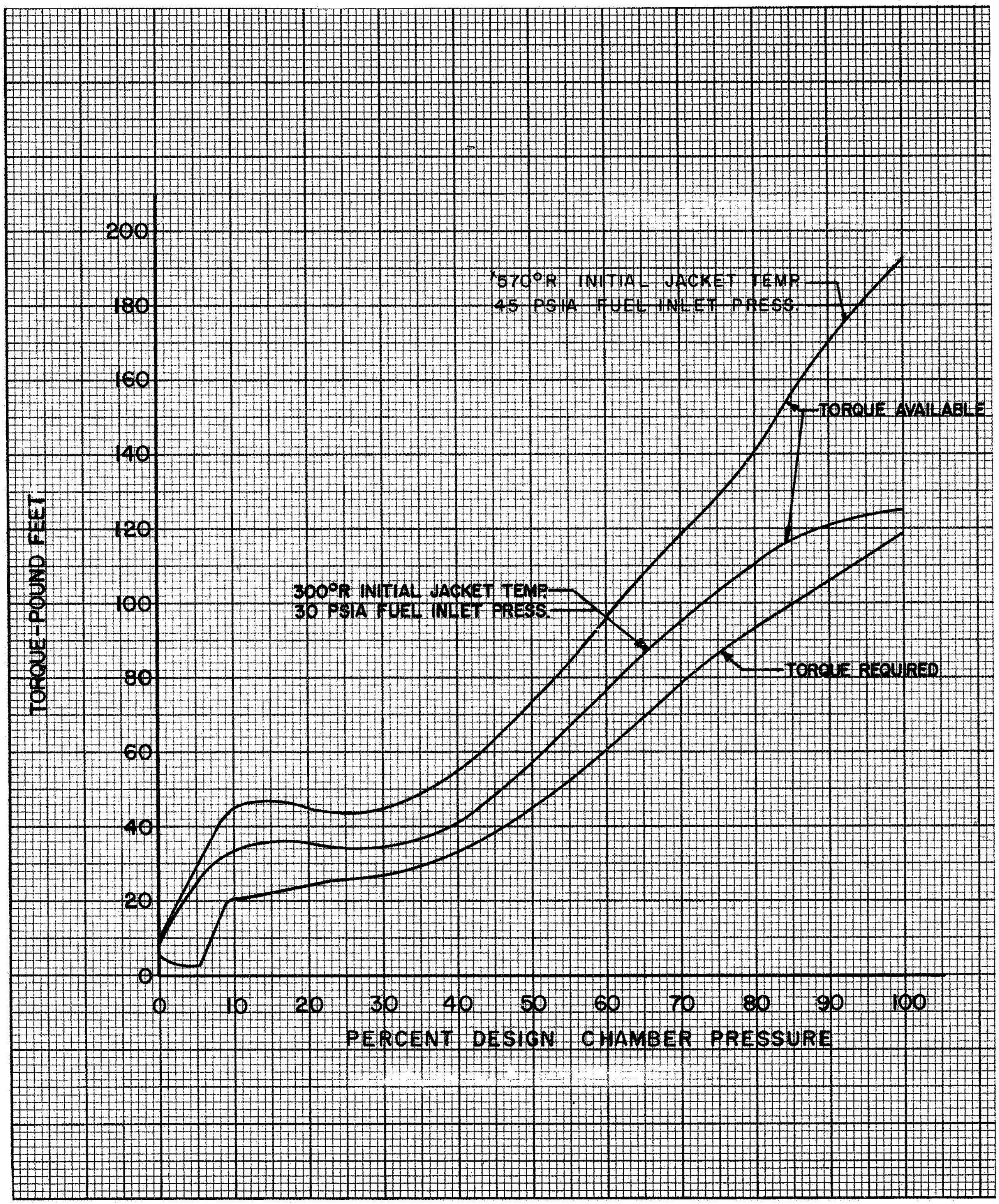


Figure D-1. Starting Torque Characteristics DF 15421

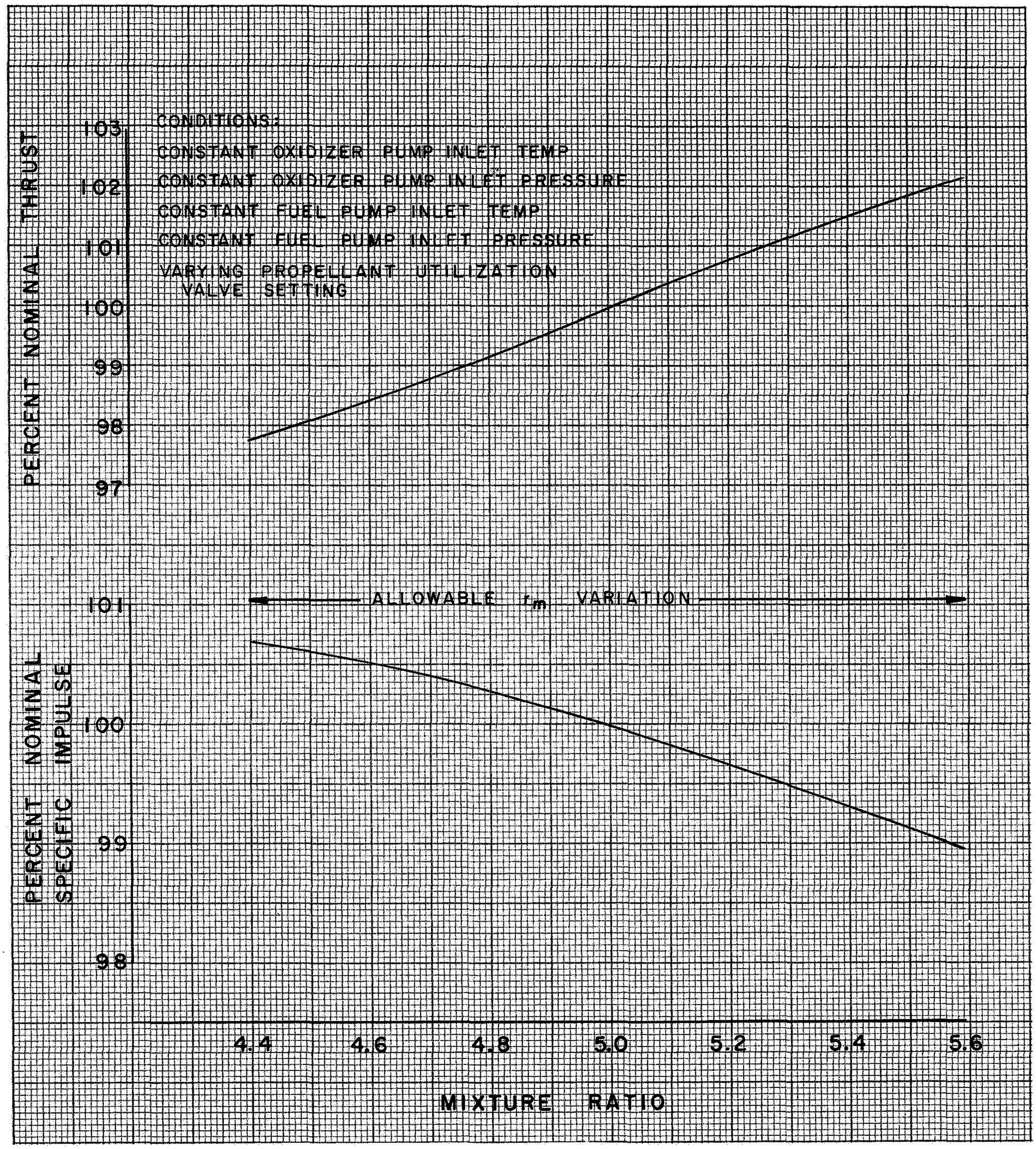


Figure D-2. Estimated Effect of Mixture Ratio on Thrust and Specific Impulse   DF 18332

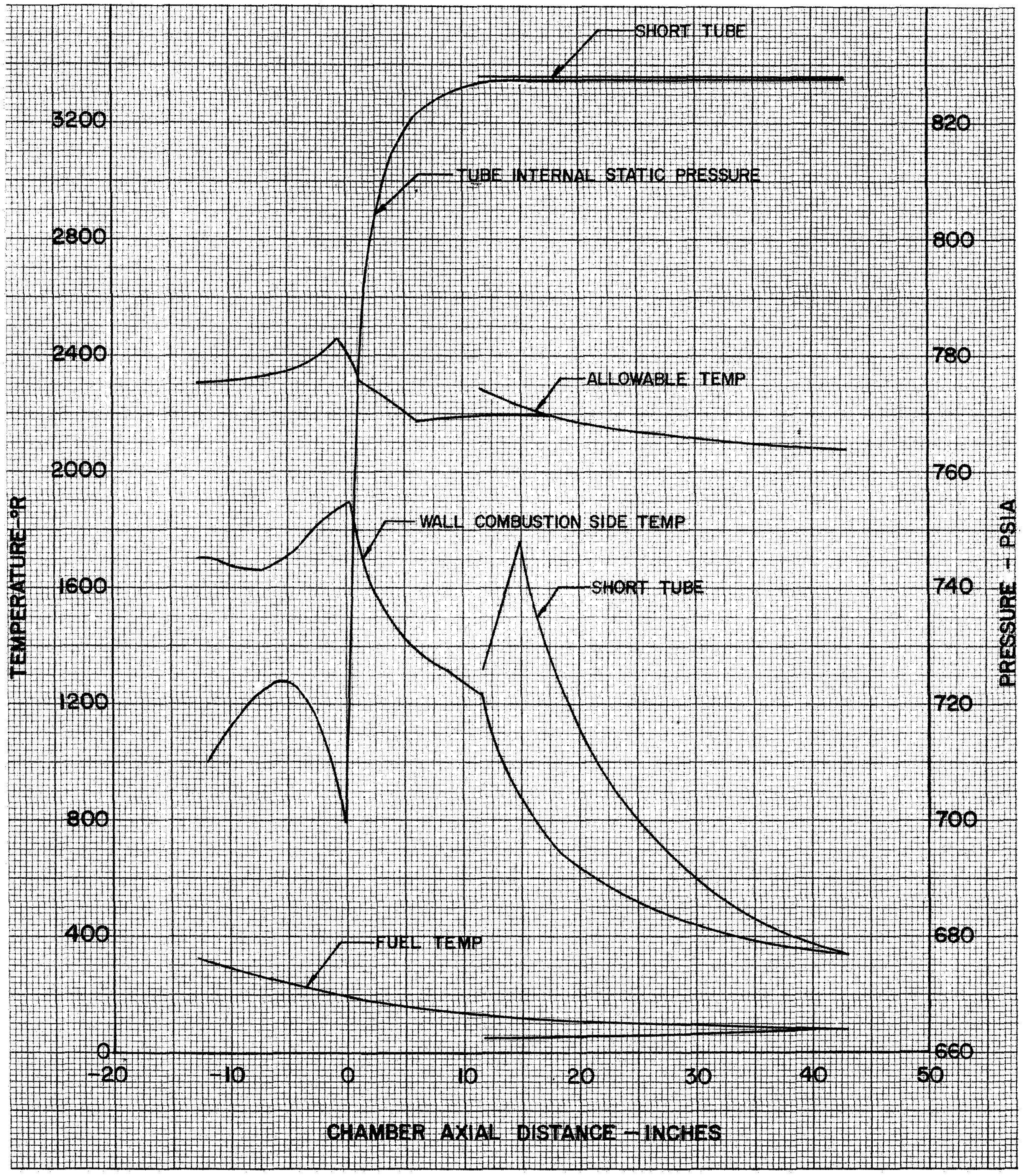


Figure D-3. Calculated Thrust Chamber Tube Temperatures and Pressures

DF 15423

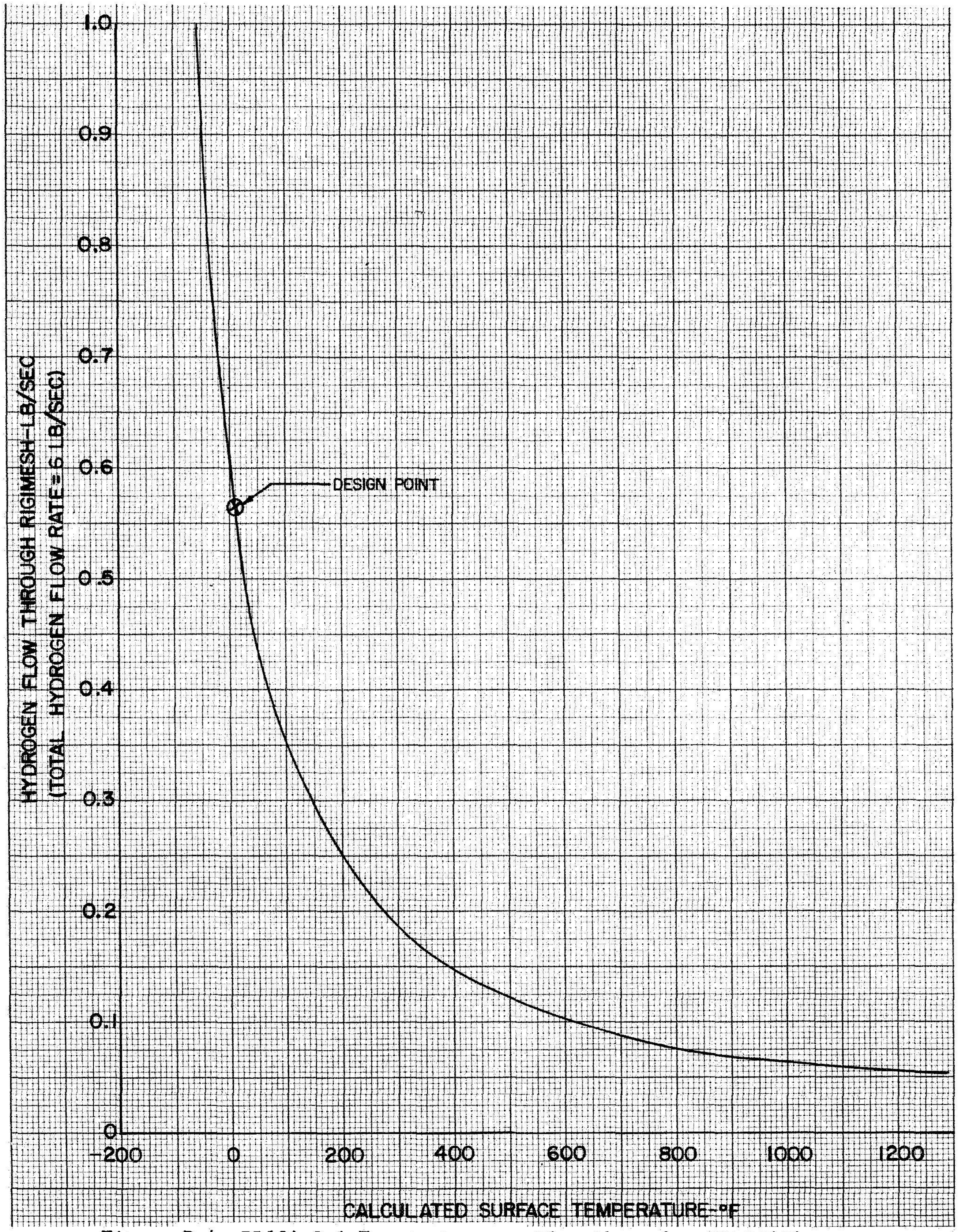


Figure D-4. RL10A-3-1 Temperature vs Flow through Injector Face DF 15424